



Scientific assessment for urban air mobility (UAM)

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Abstract

This review article is the revised and expanded version of the Scientific Assessment for UAM document that the urban air mobility (UAM) working group of the International Forum for Aviation Research (IFAR) developed at the request of the International Civil Aviation Organization (ICAO). The assessment began with a study of the industry landscape, which includes an overview of existing market studies, proposed aircraft designs and concepts, and potential paths for industry evolution. The subsequent scientific assessment, developed through cooperative efforts among international domain experts, captures 17 focus areas relevant to UAM. Each focus area presents opportunities for further research. The assessment was delivered to the ICAO in 2023. This revised and expanded version reflects the UAM domain's status quo, incorporating the most recent developments and trends identified in 2024. Key takeaways include: the need for further study of the impact of autonomous systems on the industry; infrastructure requirements (including vertiports and weather sensing) to support the industry sector; and data requirements (covering domains such as cybersecurity, emissions, and safety) to ensure safe and scalable UAM operations.

Keywords Advanced · Innovative · Urban Air Mobility · UTM · Autonomy · Vertiport

This assessment was originally conducted by IFAR AAM WG for ICAO under the umbrella of the IFAR-ICAO collaboration agreement. Named here are the editors of the revised journal paper version of the assessment. See the full list of contributing authors in author contribution section.

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Abbreviations

AAM	Advanced air mobility	EUROCAE	European Organization for Civil Aviation Equipment
ACAS	Aircraft collision avoidance system	FAA	Federal Aviation Administration
ACCS	Aviation carbon calculator support group	FAL	Facilitation program
ACI	Airports council international	FAR	Federal aviation regulation
AD	Aerodrome	FESG	Forecast and Economic Analysis Support Group
AI	Artificial intelligence	FLTOPSP	Flight ops panel
AIA	Aerospace Industries Association	FRMS	Fatigue risk management systems
AIM	Aeronautical information management	FTG	Fuels task group
AIRP	Airworthiness panel	GAMA	General Aviation Manufacturers Association
ANC	(ICAO) air navigation commission	GANP	(ICAO) global air navigation plan
ANSP	Air navigation service provider	GCAS	Ground collision avoidance system
APAC	Asia–Pacific	GCS	Ground control station
AS	Automated systems	GHG	Greenhouse gas emissions
ASA	Aviation satellite account	GNSS	Global navigation satellite system
ASBUs	Aviation system block upgrades	GPS	Global positioning system
A-SMGCS	Advanced surface movement guidance and control systems	GRAIN	Global resilient aviation information network
ASP	Aviation security policy	GUTMA	Global UTM Association
ASTM	American Society for Testing and Materials	IAM	Innovative air mobility
ATC	Air traffic control	IASMS	Intime aviation safety management system
ATF	Assurance technical framework	IATF	International aviation trust framework
ATM	Air traffic management	ICAO	International Civil Aviation Organization
ATM-X	Air traffic management – exploration	IEEE	Institute of Electrical and Electronics Engineers
AURA	Advanced ultra reliable aviation	IFAR	International Forum for Aviation Research
A2G	Air to ground	IFPP	Instrument flight procedures panel
BME	Budapest University of Technology and Economics	IFR	Instrument flight rules
BVLOS	Beyond visual line of sight	ILOT	Łukasiewicz Research Network – Institute of Aviation
CAAM	Canadian advanced air mobility consortium	INCAS	National Institute for Aerospace Research
CASA	Civil Aviation Safety Authority	ISG	Impacts and Science Group
CAT	Commercial air transport	ISO	International Organization for Standardization
CBTA	Competency-based training and assessment	IT	Information technology
CIRA	Centro Italiano Ricerche Aerospaziali	JARUS	Joint Authorities for Rulemaking on Unmanned Systems
COCBO	Cooperative oversight for cross-border operations	JAXA	Japan Aerospace Exploration Agency
CSIR	Council for Scientific and Industrial Research	KARI	Korea Aerospace Research Institute
CNS	Communication, navigation, and surveillance	LTAGTG	Long term aspirational goal task group
CNSI	Communication, navigation, surveillance, and information	MBSE	Model-based systems engineering
ConOps	Concept of operations	MDG	Modeling and databases group
CTOL	Conventional take-off and landing	MOC	Means of compliance
C2	Command and control	m:n	Many to many control
DAA	Detect and avoid	NASA	National Aeronautics and Space Administration
DEP	Distributed electric propulsion	NRC	National Research Council Canada
DLR	German Aerospace Centre	NLR	Netherlands Aerospace Center
DO	Document order	OEM	Original equipment manufacturer
EASA	European Union Aviation Safety Agency	ONERA	Onera the French Aerospace Lab
EIS	Entry into service	OPS	Aircraft operations
eVTOL	Electric vertical take-off and landing		

OT	Operational technology
PANS	Procedures for air navigation services
PBN SG	Performance-based navigation study group
PIC	Pilot in command
PKI	Public key infrastructure
PN	Protection needs
PNT	Positioning, navigation, and timing
PTLP	Personnel training and licensing panel
PSU	Provider of services for UAM
RAM	Regional air mobility
RPA	Rules of particular applicability
RPAS	Remotely piloted aircraft systems
R&D	Research and development
SAF	Sustainable aviation fuel
SAIL	Specific assurance and integrity level
SARPs	Standards and recommended practices
SC SEG	Sustainability certification schemes evaluation group
SATCOM	Satellite communication
SC-VTOL	Special condition for VTOL
SDOs	Standards development organizations
SDSP	Supplemental data service provider
SESAR	Single European Sky ATM Research
SG	Subgroup
SIP IG	Safety information protection implementation group
SMS	Safety management system
sUAS	Small uncrewed aircraft systems
SUMP	Sustainable urban mobility plan
SVO	Simplified vehicle operations
TF	Task force
TLOF	Touchdown and lift-off
TRG	Training
TRL	Technology readiness level
UAS	Uncrewed aircraft system
UAM	Urban air mobility
UKRI	United Kingdom Research and Innovation
UML	UAM maturity level
UTM	UAS traffic management
VFR	Visual flight rules
VFS	Vertical Flight Society
VTOL	Vertical take-off and landing
VTT	Technical Research Center of Finland
VZLU	Czech Aerospace Research Center
V2V	Vehicle to vehicle
WG	Working group
XBT	Cross-border transferability
3D	Three-dimensional

1 Introduction

UAM represents a revolutionary approach to urban transportation that utilizes advanced aircraft technologies to provide safe, secure, efficient, sustainable, and scalable air transportation for cargo passengers as well as air operations in urban environments and their surrounding areas, enabled by new technologies and integrated into multimodal transportation systems. As cities worldwide confront increasing congestion, pollution, and the need for rapid transit, UAM offers a promising range of solutions to these challenges.

UAM is an essential part of a broader concept known as advanced air mobility (AAM) [1] or innovative air mobility (IAM) [2] in many regions worldwide. AAM represents a rapidly emerging sector within the aerospace industry, dedicated to the safe and efficient integration of novel aircraft, referred to as new entrants, into established airspaces. IAM is a concept intended to accommodate operations with novel aircraft designs that offer new air mobility of people and cargo, particularly within congested (urban) areas, based on integrated air and ground-based infrastructure. This work details considerations relevant to multiple air mobility concepts.

To develop the vision of AAM and explore its future, ICAO established the AAM Study Group in 2023. Yet in 2020, IFAR and ICAO agreed to explore how to foster interaction between the two organizations. There was mutual interest in establishing a collaboration between IFAR and ICAO to connect the scientific community and ICAO better, especially as new and disruptive technologies promote rapid changes in aviation. The Declaration of Interest, which was signed during the 11th IFAR Summit, established the grounds for exploring ways to accelerate and improve the practical assessment of new aviation technologies and innovations. Based on this declaration, IFAR established a working group on UAM, with ICAO participating as an observer. The working group has developed the first version of the Scientific Assessment for UAM which was provided as input to ICAO's AAM Study Group. Increasing global harmonization while maintaining flexibility for local adaptation will enable the safe scaling of the AAM industry worldwide. In contrast, a lack of harmonization will result in a longer worldwide timeline to fully scaled AAM operations. Therefore, IFAR continuously investigates various aspects relevant to the ICAO mandate. One of the outcomes of such processes is this work, which is the revised and expanded version of the Scientific Assessment for UAM.

The Scientific Assessment for UAM focuses on sharing harmonized, consensus-driven products with ICAO that provide scientific insight into the state of AAM and use cases such as UAM. The IFAR international working group participants work across scientific areas to provide

perspectives of international researchers on industry considerations, such as the state-of-the-art and future needs. Outputs from focus area teams, including the key takeaways, gaps, and open research areas, were delivered to the ICAO Secretariat. Additionally, the IFAR routinely participates in workshops to brief preliminary results, share initial ICAO reactions, and mature messages within the focus areas. These workshops enable the IFAR to further research and development (R&D) initiatives and interact with ICAO leadership and working groups by contributing to the various ICAO initiatives.

The IFAR comprises researchers from 27 countries, and its experts bring varying domain knowledge. Contributions were solicited from researchers with expertise in topics relevant to UAM, leading to the formation of 17 teams. Additionally, the outputs from each team are at different maturity levels, and these outputs are expected to evolve as needed. For example, some focus area teams have interacted with their relevant ICAO Secretariat counterparts, incorporated their feedback, and provided the updated outputs in this document, while other teams have not.

Technical focus areas specify the scope and relevance of the findings presented, and further iterations of the findings will expand the scope beyond UAM-specific details. The Scientific Assessment considers available literature (see e.g. review papers [3–7]) but extends that by capturing a summary of the outputs from the IFAR expert teams covering each focus area of UAM. Although these outputs represent the consensus of each team, it is noted that each IFAR member nation did not participate in each team, and there is no expectation that ICAO will endorse this document or accept it as a formal input.

This scientific assessment aims to provide a comprehensive analysis of the current state and future potential of UAM. It encompasses a multidisciplinary evaluation, integrating insights from aerospace engineering, urban planning, environmental science, and regulatory frameworks. The assessment is structured to address key areas, including technological advancements, infrastructure requirements, safety protocols, environmental impacts, and socio-economic implications.

By synthesizing the latest R&Ds, this assessment seeks to inform policymakers, industry stakeholders, and the academic community about the critical factors influencing the successful implementation of UAM. It also highlights the collaborative efforts needed to overcome technical and regulatory hurdles, ensuring that UAM can be seamlessly integrated into the urban transportation ecosystem.

The ICAO and the IFAR will continue to explore innovation trends, their application to aviation, and how they can help advance our respective areas of work. The Memorandum of Understanding signed between the two organizations

on 5 April 2022 enables and guides further collaboration. Deepening collaboration enables the ICAO and the IFAR to tackle complex challenges that improve the quality of life, maintain public confidence in aviation, and support international sustainability efforts.

2 Industry assessment

Several market studies have analyzed the potential opportunities and market size for UAM, considering different use cases and geographical locations. Most studies focus on passenger-carrying use cases, including air taxi [8], airport shuttle [8–10] and air metro operations [10–12] within metropolitan regions as well as intercity/regional transport operations [8, 10, 11]. Additionally, some studies have considered the use of UAM for last-mile delivery [9], business aviation operations [10] and medical and emergency services [10–12]. Localities analyzed include Asia–Pacific [8], UK [11], Canada [10] and the U.S. [9, 12]. A worldwide market value of \$510 billion is projected by 2040, with the greatest revenue value expected for operators and infrastructure providers [11].

Traditional aviation companies, start-ups, and research institutions around the world have proposed, designed, and developed numerous types of UAM aircraft. Existing designs span various levels of maturity, with some undergoing certification processes and others existing purely as conceptual frameworks. A comprehensive list of existing designs can be found in the Vertical Flight Society (VFS) eVTOL (electric vertical take-off and landing) Aircraft Directory [13]. The proposals vary substantially in terms of passenger capacity, propulsion, airframe, automation level and operational requirements. Notable designs in more advanced stages of development include vectored thrust aircraft, which orient their thrusters for lift and cruise depending on flight phase; lift+cruise aircraft, which use separate thrusters for cruise and lift without thrust vectoring; and multicopter aircraft, which typically use more than two thrusters for lift. In terms of capacity, they vary from single-passenger configurations to larger aircraft capable of carrying 4–7 passengers. Range also differs significantly, from short trips of 30–40 km to longer distances of up to 300 km. The majority of designs feature all-electric propulsion systems, targeting lower environmental and noise impacts. However, for configurations aimed at longer-range missions, hybrid-electric propulsion systems are anticipated in the industry evolution, as well as the possibility of hydrogen propulsion further in the future. Certification programs are in progress across many nations, and some regulatory environments will be friendlier than others. While significant progress has already been made in the certification of aircraft systems for piloted operations,

certification of remotely piloted aircraft and automation systems is broadly more challenging and will take longer.

Industry stakeholders have also worked to develop concept of operations (ConOps) proposals [14–17] describing the UAM operational environment and its evolutionary path. There is consensus that initial UAM operations will be conducted by conventionally piloted aircraft, leveraging much of existing airspace structures and Air Traffic Control regulations, under low density and complexity levels. However, for UAM operations to scale and reach a mature state, changes to the governing regulations, infrastructure, and automation technologies will be required, allowing for complex and dense flight networks that include remotely piloted operations. To facilitate this evolution, there is potential to leverage the small, unmanned aircraft system (sUAS) traffic management (UTM) developments, including their application to support initial operations. However, this requires a deeper understanding of commonalities and opportunities for synergetic technological development. It is also anticipated that initiating rural and cargo transport operations before urban and passenger transport operations will become a generalized best practice across all emerging markets, with the ability to perform robust data gathering campaigns on new configurations that can minimize risk or negative impact to the market and general public.

3 Methodology of the scientific assessment

The IFAR began the Scientific Assessment for UAM by establishing focus areas capturing technology, operational, and societal acceptance. The IFAR identified and engaged technical experts from research agencies around the world. Leads for each focus area were identified and the teams of experts then began developing content for their focus areas. The teams captured information such as an overview of their focus area, a state-of-the-art assessment, a gap analysis, and any open research areas that still exist. Additionally, teams collected relevant research publications on their focus areas and summarized their findings as key takeaways. The teams briefed the ICAO Secretariat throughout the Scientific Assessment process and incorporated comments received before delivery of the assessment.

3.1 Overview of output template

The outputs from each focus area team are captured in the sections below. Each output is organized into the following subsections:

- *Overview of technology/operational/societal acceptance area* Provides a high-level overview of current

technologies, standards, and policy relevant to the focus area.

- *State-of-the-art assessment* Provides the more detailed findings of the technical team.
- *Gap analysis* Describes technology, standards, and policy gaps for UAM operationalization relevant to each focus area.
- *Open research areas* Captures the technical team questions and open areas for further research.

3.2 Scientific assessment gaps

The Scientific Assessment – broad and diverse in scope – is expected to include gaps in research. Gaps may exist within the focus areas researched by the technical teams, but there may also be gaps in the form of topics not captured within the scope focus areas of the Scientific Assessment.

4 Technology

UAM depends on technological advances such as, but not limited to, electrification, battery capacity, increasingly autonomous functions, and connectivity. These advances impact the ability for aircraft to use electric propulsion, store energy, use autonomous task as well as system level management, and provide continuous communication as well as surveillance to support airspace operations. It is important to note that adoption of technologies must be considered from the perspective of safety, security, infrastructure, aircraft, and airspace system requirements to enable advanced air mobility. The following sections provide specifics related to aircraft, propulsion system, autonomy, airspace integration, safety, infrastructure, security, and communication, navigation, and surveillance considerations needed to support these operations. Additionally, each consideration will offer state-of-the-art, gaps to enable future, and research needed to address overall requirements. Clearly, technological aspects influence societal acceptance. For example, electric propulsion may help reduce noise generated by these aircraft thereby leading to better acceptance than just helicopters.

4.1 Aircraft overview

This chapter addresses the general design and operational aspects of UAM aircraft. A discussion on aircraft configuration and the current certification approaches are presented. Operational aspects including conflict avoidance, noise, and cost are highlighted. Infrastructure, including vertiports and pilot training are presented from an aircraft point of view.

One of the significant advancements that enables UAM is electric propulsion and use of batteries. Electric propulsion, in general, will reduce the noise aircraft generates and lower the number of parts required in aircraft. Configurations differ from legacy traditional rotorcraft with less maturity in some key areas [7, 18], especially in the form of combination of wing and rotors, number of passengers; size of cargo; number and arrangement of rotors; motors; engines and/or propellers; blade hinges; trim control; vibration; gear boxes; and noise. The introduction of multiple, constantly changing forcing frequencies creates a paradigm shift with many differences from conventional/traditional rotorcraft. Distributed electric propulsion (DEP) may generate lower noise levels but can still be quantified as annoying to bystanders [19].

Many researchers and organizations are also promoting simplified aircraft designs so that pilot training could occur faster, and aircraft will be easier to learn and operate.

Regarding ability to operate uncrewed aircraft, an equivalent of see and avoid is needed – which is referred to as detect and avoid. The detect and avoid will allow sensor-based detection of cooperative as well as uncooperative aircraft in the airspace. The actual collision avoidance systems (Detect and Avoid/DAA) are not yet used in dense aircraft environments as technology or functional requirements have not been finalized. DAA will be challenged by the emergence of large numbers of uncrewed UAM aircraft in the urban environment, flying at low altitudes to many different landing sites [20]. The DAA system, for obstacles in the flight path and for birds [21, 22], may also require further attention.

4.1.1 State-of-the-art assessment

To this date, there have not been any eVTOL that has received certification by the Federal Aviation Administration (FAA) and/or European Union Aviation Safety Agency (EASA). China became the first country to grant certification to eHang's eVTOL. The details of certification are not readily available. Several demonstration flights have been conducted in the United States, Europe, Japan, India, and China. In the United States and Europe, several companies have received experimental certification and are making progress towards certification. The aircraft manufacturers are conducting operational trials to collect data towards their certification path. However, the access to funding needed all the way to certification has been a challenge for a few companies. There are many different aircraft being developed (from conceptual design to flight test) without an emerging leading aircraft configuration [23] – unlike the legacy rotorcraft market that has remained fairly consistent in aircraft configuration. Because initial commercial operations

are not yet underway, several years are necessary to reach scaled, routine commercial operation (considering certification timelines, mass production, infrastructure, etc.) [9, 12, 24]. Flight tests, development, and demonstration of various aircraft prototypes are underway. There are finite resources in four main factors: (1) availability of qualified pilots [25, 26] (2) cost of aircraft [27, 28], the potential number of aircraft sold [29, 30], and the ambitiously low consumer cost benchmark (as low as USD 3 per passenger mile [31, 32]) (3) availability of specialized airport infrastructure (vertiport) [33]; and (4) air traffic control capacity [34]. Pilot augmentation technology would help to reduce pilot formation time and provide sufficient qualified pilots [35]. The presence and number of pilot(s) on board furthermore is proportional to the passengers' willingness to travel [36].

Companies such as Joby Aviation, Archer, and Wisk are focused on vertical take-off and landing configuration with hover capabilities whereas others such as Electra Aero, and Pipistrel used short or conventional take-off and landing configuration which extends their range.

4.1.2 Gap analysis

There is a lack of quantifiable data regarding the urban population's level of annoyance induced by the frequent passage of aircraft [37, 38]. Common standards with documented methodology for noise and safety regulations are needed for UAM designs. EASA already published guidelines on noise measurements for sub 600 kg UAS [39] and environmental protection technical specifications for VTOL aircraft [40]. The effect of feasible noise mitigation strategies on the performance reductions for low-noise aircraft can only be developed once those standards become available. Additionally, there will be a need for improved aeromechanic predictive tools in the early design stage for UAM aircraft. There are many design methodologies with different approaches and varying levels of fidelity available [41–43], but these studies tend to come to their own conclusions, based on different assumptions. Standardized performance evaluation methodology for flight segments and performance standards in urban environments for UAM aircraft must be defined. Arguably, the key performance issue to be resolved, due to the various forms of (partially) electric powertrains, is the setting of energy reserves [44–47]. New design requirements for vertiports, including acceptable flight paths when approaching and departing from different take-off and landing sites with sense and avoid capacity, are also required. Published guidelines from the FAA [48], EASA [49] and JCAB (Japan Civil Aviation Bureau) [50] are available. The same level of safety as the existing air transport systems (according to their category) should be achieved, as formulated in the EASA SC-VTOL [51] (and

associated published MOC [52]) and the FAA approach to certify aircraft using CFR Part 21.17(a) [53]. However, this means high cost, making this level of safety less acceptable from an economical viewpoint. As different opinions exist within the industry, a consensus should be obtained.

4.1.3 Open research areas

1. Is production of aircraft at low cost satisfying the severe flight safety regulations (possibly due to the small numbers produced)?
2. What is the time period required for the implementation of the various technologies needed for the different aircraft configurations?
3. What are the noise standards and possible aircraft restrictions needed for both aircraft configuration and social acceptance?
4. Can the infrasound generated by electric propulsion be minimized effectively?
5. How is the adaptability of different configurations as it relates to the various usage scenarios?

4.2 Propulsion and energy

Propulsion systems and the related primary energy storage is one of the key technical challenges related to UAM aircraft. While the technologies used are not new, UAM presents unique challenges that need to be addressed. This chapter presents the different type of propulsion methods being considered today, along with the identified specific system characteristics and technical elements that need further development.

To successfully operate in an urban environment and confined areas, many believe that UAM aircraft must be capable of VTOL to operate, and the aircraft should not contribute to the emissions problems in most cities. Some researchers also consider (S)STOL (super short take-off and landing) for sub-urban or intercity operations, but there is no general agreement in this direction [54]. These requirements present unique technical challenges which have resulted in designs for UAM aircraft that are VTOL and use electric or hybrid-based propulsion systems. Vertical take-off and landing add to energy requirements, and aircraft using a large number of propellers are less efficient in hover than traditional rotorcraft resulting in payload, range, and endurance performance limitations [55–57].

The major barrier to increased aircraft performance is the poor specific energy of batteries compared to liquid hydrocarbon fuels, coupled with the need for a high-energy discharge rate for hover. Many current VTOL UAM aircraft are electric, with some configurations exploring hybrid-electric

systems to extend range. There are proponents of hydrogen as a possible energy source with great promise, but that area is developing on a longer timeframe. There are also proponents of using sustainable aviation fuels (SAF) to reduce emissions. Any type of novel refueling/recharge system will require significant investments in technology and infrastructure. Ancillary propulsion system considerations such as high-voltage system safety [58], battery monitoring and replacement [59], fire hazard containment [60], and thermal management must all be addressed during certification. Lithium-ion batteries are typically installed in current eVTOL prototypes [61]. Their gravimetric energy density lies between 150 and 350 Wh/kg on pack-level [62].

Many eVTOL and eCTOL companies are building their own battery packs to support the aircraft operation. The energy density range is typically anywhere from 230 to 480 Watt-hours per kilogram. Due to sensitivities related to intellectual property protection, the exact energy density data is not readily available and continued improvements in energy density remains an important area of research. In comparison, the jet fuel's energy density is about 12,000 Watt-hours per kilogram.

4.2.1 State-of-the-art assessment

Electric propulsion systems are operational and in demonstration flight tests in many different types of VTOL aircraft. Many advances are needed in power density [63], reliability [64, 65], packaging, monitoring, servicing, and ground infrastructure to advance to scaled commercial operations for electric propulsion aircraft. Electric motors, no matter the power source, give off low-grade thermal heating even in the best of design conditions [66]. Cooling systems for the motors and shedding the excess thermal energy that is generated without adding significant weight is a serious design challenge for the aircraft [67]. Hybrid-electric systems can extend the range of UAM aircraft, and hybrid-electric systems are under evaluation particularly for aircraft that are targeting longer range markets, such as intracity transportation [68–70]. Hydrogen fuel-cell propulsion systems are proposed as an alternative to increase range [71] but have not been demonstrated in VTOL systems, although studies are available, including cost estimation [72]. For hydrogen systems, a major limitation is physical space on the aircraft for the fuel cells and storage tanks. The hydrogen/fuel-cell technology lags behind battery technology but may be more revolutionary, and the development of hydrogen alternatives is on a longer timeframe than battery-based systems. Neither electric nor hydrogen advanced propulsion concepts are currently being used in commercial operations.

4.2.2 Gap analysis

Battery technology development is needed to increase the specific energy, power density, and the charge/discharge rate. In the near term, researchers predict 500–550 Wh/kg specific energy by 2030 [73], and as high as 5000 Wh/kg theoretical values have been identified (O₂/Li chemistry [74]). Battery improvements are also needed in smart energy storage/management [75], rapid recharge capability [76], as well as weight, safety [77, 78] reliability, cost, recycling [79] and other factors. Enabling technologies at the system level are needed to package the batteries for optimum efficiency and safety. Improvement in high-voltage hybrid-electric generators is for efficiency, although performance is needed as well. Broad updates in infrastructure and economy are needed to enable hydrogen benefits [80]. Also, the net emissions of pure electric aircraft compared to hydrogen fuel cells needs further analysis. Certification requirements for UAM VTOL aircraft are still evolving. Some requirements indicate that components of the propulsion system may require the highest levels of reliability to meet expected safety requirements. Existing UAM aircraft concepts may have difficulty meeting a high reliability requirement. Standardization of power system connections and charging infrastructure is needed for scaled operations.

4.2.3 Open research areas

1. Can new motor designs have higher reliability than current designs?
2. Can advanced thermal management systems that are lightweight work in hover and low-speed flight conditions?
3. What is the mechanical fatigue of motor components (e.g., motor windings due to high-cycle thermal loads)?
4. Can electric components, power distribution, power quality, high-voltage systems, motor design, and integrated thermal management systems be matured to support UAM?
5. What can be learned about battery life cycle, charging/discharging, safety after impact, and monitoring systems for prognostic maintenance?
6. Can advancement of hydrogen fuel cells support hydrogen safe handling and storage?

4.3 Autonomy

Various levels of autonomy options exist and have been planned by industry; these range from a task-level autonomy to full-aircraft autonomous operation [81]. The Autonomous Systems (ASs) are applied at all flight stages and

functions, including mission management, strategic flight-path planning, trajectory execution, tactical operations, and systems management in nominal and non-nominal situations [82–87]. A key objective in applying ASs to UAM is enabling changes to the authority of the human operator or pilot [14, 81, 88]. On a larger scale, applying ASs may bring changes in the roles and responsibilities of the involved actors, enabling new operations and expanding the UAM markets. An eventual goal is to enable safe, fully autonomous aircraft operation with a small ground staff supervising large numbers of aircraft [89]. Full autonomy would imply that the system makes its own decisions and actions without any human intervention. Such capability would be particularly impactful for UAM, given their small payloads compared to transport aircraft. In addition to onboard technologies, airspace system updates are critical to enabling and accelerating the deployment of aircraft with a higher degree of autonomy. These updates include technologies such as sensing, processing, and communicating, as well as flight rules leveraging these capabilities [88].

4.3.1 State-of-the-art assessment

Currently, regulations vest final responsibility for the safety and operation of the aircraft in the pilot in command (PIC) [14]. The PIC must be able to operate the aircraft without support from automated systems to the maximum possible extent. This philosophy significantly elevates minimum pilot qualifications and sets requirements for human performance while often reducing targeted automation capabilities, particularly in non-nominal contingencies [90]. UAM research develops towards adaptive automation, meaning that, depending on the situation and flight phase, certain tasks can be distributed between the AS, the pilot or a (remote) pilot [89] envisions the development of ASs that perform designated functions with better performance and higher safety than pilots in all situations that are not shown to be highly improbable. Thus, the ASs are to ultimately gain the responsibility for control functions and allow pilots to be out of the control loop thereby making irrelevant pilot workload and qualifications. While it is expected to achieve near full autonomy within 15 years [91], companies are pursuing various strategies to achieve this objective, including going “direct to autonomy” [92] and more incremental strategies that change the balance of pilot and automation authority and responsibility [91], as well as adoption of AI-enhanced systems [93]. Currently, limited analysis or data has been published documenting the viability and progress of these strategies.

4.3.2 Gap analysis

The regulatory requirements for AS relative to candidate functions, performance, reliability, and design assurance requirements are currently uncertain [86]. The means of verifying compliance with assurance requirements for non-deterministic algorithms are currently a gap [94]. Emerging ASs perform specialized tasks, and the underlying technologies do not fully replace the general intelligence essential to aviation safety. As such, human-automation teaming and associated challenges will remain important for the foreseeable future, particularly for concepts envisioning remote aircraft supervisors [89]. The current regulatory structure governing aircraft, airmen, and flight operations is predicated on human-centric operations and demonstrated success [90]. Significant revisions to this structure are required to take full advantage of ASs [89, 91]. As rapidly evolving ASs expand the scope of potential human-automation teaming concepts, the development and application of appropriately integrated, flexible, and effective regulations will become increasingly challenging and important [89]. Finally, as actual operations are required to fully validate the capabilities and limits of evolving ASs, developers, and regulators need to cooperatively develop strategies allowing operations and learning in applications with risk tolerances consistent with the underlying concept maturity [14]. In addition, standards for documenting and applying data from these early operations to other use cases, nominally with higher assurance and safety requirements, are needed [14]. One of the key gaps in understanding is how autonomous systems handle unexpected situations that human pilots, air traffic controllers, dispatchers, and others address in current operations. To ensure that autonomous functions, whether at a task level or at full aircraft level, will perform safely, they will need to be proven to operate safely under off-nominal, contingency, and corner cases.

4.3.3 Open research areas

1. What are software verification methods for UAM artificial intelligence and machine learning-based systems?
2. What kind of novel architectures and assurance methods are needed for complex ASs and operations, including automation of abnormal operations (e.g., run-time assurance, overarching properties, fault tolerance, reliability)?
3. How to achieve safe distribution and allocation of decision-making between aircraft, operators, control stations, and airspace infrastructure?
4. What pilot/crew qualification and certification are required to match the different levels of autonomy?

5. How to achieve a balance of diversity of AS design, competition, standardization, and burdens on regulators?
6. How to achieve airspace system development that enables and accelerates the development of ASs and their adoption?
7. How to harmonize standards and regulations to step beyond a human-centric approach and, at the same time, to maintain or increase safety and scalability?
8. How to qualify operators and pilots to be able to supervise automated systems?

4.4 Airspace integration and UAS traffic management (UTM)

The UAM concept is focused on, but not limited to, rules, procedures, and technologies that enable the movement of cargo and passenger aircraft in the urban environment. The FAA and NASA have defined a broader term, AAM [1], which covers regional and interregional operations as well. There are many concepts of operations in development, as given by the FAA UAM ConOps v2.0 [15], the NASA UAM Vision ConOps [15], and U-space ConOps created by the CORUS-XUAM Project in Europe [14], and the ConOps for AAM in Japan [16] which outline various airspace integration implications and solutions.

Most UAM airspace models are based on airspace categorization and geofencing, and they can be both unstructured (free flight) and structured (corridors, tubes, layers, lanes). Comprehensive analyses of different UAM operation concepts focusing on traffic coordination and risk assessment have been published [34, 95]. While there are various criteria used for quantitative evaluation, all concepts consider whether management by exemption helps with the scale or not without overloading air traffic controller workload.

While harmonization is required at an international level for these ConOps, a key characteristic emphasized across these documents is that the growth of the UAM industry will increase traffic density and frequency in certain areas. This growth and unique set of performance characteristics will introduce operational challenges that current global ATM systems are unable to support. This technology area is focused on identifying procedures, constructs, and technologies needed to seamlessly integrate UAM operations into existing airspace environments while allowing for regional considerations. The main point of UTM (UAS traffic management) and U-Space efforts is migration from a centralized system to a federated system where third-party service suppliers can also provide key services such as communication, flight planning, strategic deconfliction, weather data, 3D maps, etc. The basic lessons learned from UTM and U-space trials are that if we have digital, cooperative, intent sharing with prescribed application protocols, management

by exception, service-oriented architecture with third-parties providing services then we are able to scale these operations without burdening the air traffic and overloading air traffic controllers' workload.

4.4.1 State-of-the-art assessment

Novel airspace integration policies and constructs for passenger-carrying UAM aircraft, either crewed or uncrewed, do not currently exist and require significant research and assessment to develop. Globally, early UAM entrants will most likely utilize existing or modified low-altitude flight rules [96], procedures, and ANSP (air navigation service provider) interactions to complete initial missions. Public good operations, such as disaster response, air ambulance, emergency good delivery and police operations have been in the spotlight as initial UAM use cases [97]. While UTM concepts have begun to be implemented across the globe, these systems are focused on enabling small, unmanned drones to access low-altitude airspace beyond visual line of sight (BVLOS) with minimal impact to the existing aviation system; however, the line between UTM and UAM operations is blurry and needs further discussion in the research community.

4.4.2 Gap analysis

The UAM airspace structures, procedures, and definitions (such as enabling the use of layers, corridors, and operation volumes) require development and description to enable scalable operations [98]. The UAM separation requirements are not currently standardized, and therefore will need to be researched and defined to support UAM operations. Technology, methods, and data structures for intent sharing must be defined for UAM operations. While lessons learned from UTM can be leveraged, there are significant differences for higher altitude and passenger-carrying operations that may imply different risk ratios for ANSPs or UAM service providers. Identification of other data services, such as weather data for the urban canyon, must be outlined along with information exchange protocols. Alongside the development of intent sharing methods and other data, a comprehensive system architecture that can be applied across the globe may be required to ensure that operations can occur effectively across nations. Additionally, roles and responsibilities between different UAM ecosystem entities should be defined for varying levels of automation – including UAS and remotely piloted aircraft systems (RPAS) operations – to enable long-term UAM operations. The need for a harmonized framework, global provisions and guidance have been recognized by ICAO as well and an expert study group on advanced air mobility has been established [1].

4.4.3 Open research areas

1. What are the information requirements, procedures, and technologies needed between UAM operators and existing ATM services to enable early and long-term operations? How do airspace systems or supporting services interoperate for diverse operations in the same geographic areas?
2. Can airspace integration methods, systems, and data structures be extrapolated from UAS, UTM, and other relevant operations (e.g., Part 121, Part 135, disaster response practices)?
3. What are the navigation and surveillance performance requirements and accuracy of these capabilities needed to enable airspace integration and monitoring of UAM operations?
4. Can separation minima be defined for UAM-UAM, UAM-sUAS, and UAM-traditional traffic?
5. What new regulations and rules will be required to establish new airspace structures and procedures for UAM operations to make them scalable while preventing overburden of existing ATM services?
6. Can responsibility for separation and conflict management be delegated to UTM/UAM service providers?

4.5 Safety management systems

Aviation is a safety critical industry. All stakeholders must adopt the appropriate safety culture and mindset to enable the safe and secure implementation of technologies and operations. Safety must encompass the entire lifecycle of aircraft, supporting systems, and direct and associated services. This chapter briefly examines SMS in a more general sense, as used in the aerospace industry today. Following that, the points specific to UAM and the current challenges and unknowns are presented.

Safety and the corresponding SMS are an integral foundation for the integration and operationalization of respective technologies as they assure their safe and secure implementation throughout the entire life cycle. The security aspects will be covered in Sect. 4.7. Safety management systems (SMS) in themselves are not an independent technology but represent a system on how to use and maintain technologies that must be laid out prior to their operation. This also includes training for the people involved [99] to ensure a certain standard of safety and security as well as monitoring and auditing mechanisms. SMS are highly advanced within the commercial aviation industry, often portraying a high degree of complexity, as SMS in classical aviation have continuously evolved over a period of more than 50 years to ensure pilot and passenger safety [100, 101]. The ICAO

Annex 19 *Safety Management* contains Standards and Recommended Practices (SARPs) for Safety Management in Aviation. Appendix 2 contains the framework for a SMS. The UAM service providers may be responsible for the most safety critical UAM operations and will need to implement SMS [102] comparable with the SMS framework as contained in Annex 19 Appendix 2.

4.5.1 State-of-the-art assessment

With ICAO Annex 19 as a basis, a viable framework for a SMS already exists for UAM operations; however, it is currently unpredictable whether additional amendments to the current framework might be required to fully encompass the UAM ecosystem into a SMS. This is mainly due to the low levels of maturity regarding the new technologies, which constitute the majority of the UAM ecosystem, and this results in insufficient data as a possible basis for new or amended regulations. Regarding UAM, regulations for safety must be considered prior to flight, managed in-flight, and assessed post-flight and requires a convergence in design and operational safety techniques which will require paradigm shifts and new standards for certification [103, 104]. The requirement for integrating increasingly automated and autonomous systems will require novel certification processes, techniques, and standards due to the increase in software executive capabilities [105]. Database management tools are helpful but not sufficient. Current data analytics are not able to predictively assess safety for UAM maturity level (UML) 4 operations [106]. The impact of security measures (e.g., for cybersecurity [107]) on safety is not well addressed in the information flows within the current SMS approach. Both the integrity of data and the availability of data to provide in-time results have never been fully addressed [108].

4.5.2 Gap analysis

The UAM service providers are currently not explicitly mentioned in ICAO Annex 19 Safety Management or in ICAO Doc 9859 Safety Management Manual [109]; therefore, which UAM service providers need to implement SMS is currently not clear and not harmonized. Additionally, the SMS of AAM/UAM service providers will rely on contractual controls and use of safety critical services provided by contractors or other organizations that are likely not all able to identify and assess operational hazards themselves. Examples include providers of Command and Control (C2)/C3 links and weather information [6, 110, 111]. Adequate guidance material (best practices) to support AAM/UAM service providers in managing risks associated with safety critical services are needed. Furthermore, the safety risks

associated with autonomous or highly automated UAM aircraft are not well understood [112, 113]. Unknown aspects must be clarified and addressed in safety management. Additionally, the highly automated systems being proposed and developed need a high level of security monitoring and analysis to assure the overall safety of the operations [114]. The intersection of safety and cybersecurity must be addressed [115] and will exist directly in hazard analysis, risks that can be realized by (a lack of) cybersecurity or the enhancement of cybersecurity measures that negatively affect safety [116].

4.5.3 Open research areas

1. Can SMS be effectively implemented for UAM with the current lack of data?
2. What safety data is really needed for an effective SMS implementation in the UAM domain, and can this data be extrapolated from sUAS and other relevant operations?
3. Is there an interdependency between (operational) data, safety, and technology development for UAM/AAM?
4. How can the safety risks of autonomous or highly automated UAM aircraft be assessed and evaluated? How to demonstrate to the authorities that operations with such UAM aircraft will be safe?
5. Can the in-time aviation safety management system (IASMS) provide in-time notification and possible mitigation of cybersecurity hazards?
6. How can IASMS and its notifications account for different levels of automation/autonomy?

4.6 Infrastructure

The development of infrastructure for vertiports is still in its infancy; however, initial low throughput operations will likely be established by modifying current infrastructure technology. It is unlikely that all infrastructure solutions employed today will be suitable to meet the future demand for UAM operations; therefore, it is assumed that the infrastructure technology solutions will need to evolve as the operations evolve. There are unique challenges associated with UAM/AAM operations and the infrastructure needed to support them. The UAM/AAM aircraft have a wide range of designs, dimensions, performance, intended use, and a variety of fuel sources. The UAM/AAM operations seek to extend beyond airport environments into nontraditional locations such as urban centers, rooftops, oil rigs, etc. Impact from a vertiport on existing operations and communities will be dependent on facility and locality; however, often the intended use to align with commercial business cases

requires higher throughput operations, which will strain the security, safety, and efficiency of existing infrastructure and technology systems [117]. Five key technology areas that need further development were identified as CNSI (communication, navigation, surveillance, and information) technologies, safety technologies, power supply and recharging technologies, security technologies, and handling technologies. Other areas for consideration of infrastructure include water and waste management, garbage collection, maintenance infrastructure, and other engineering infrastructure as examples.

4.6.1 State-of-the-art assessment

There are wide ranges of infrastructure that support aircraft operations at airports and heliports. Given the diversity of potential UAM/AAM use cases and aircraft configurations, there is no clear roadmap on the requirements necessary to support UAM/AAM operations – even at existing facilities. Current vertiport design guidance issued through an engineering brief from the FAA and a vertiport design specification from EASA, focus primarily on the design, layout, markings, and visual aids of a vertiport facility but are less detailed in the required infrastructure to support the operations. Current facilities, primarily airports, have CNSI technologies and services that support operations; however, these technologies were designed for airport environments which may not yield sufficient performance in UAM/AAM environments (e.g., urban vertiports) or at the desired operational tempo of UAM/AAM operations. While initial, low throughput operations are targeted to leverage existing infrastructure, there is a risk that lack of planning towards infrastructure development for higher throughput operations could result in significant delays towards industry timelines.

4.6.2 Open research areas

1. What are the roles and responsibilities for the vertiport manager?
2. What are the information requirements between the pilot/aircraft, vertiport, air traffic control, and fleet manager?
3. What parts of the ground operations and passenger handling should be digitized and automated?
4. What is the regulator oversight model and design assurance requirements for vertiport technologies?
5. What are the performance requirements for CNS to support autonomous and piloted aircraft?
6. What energy infrastructure is needed to support charging?

7. What are the landing and take-off support needs particularly under low or zero visibility conditions?
8. What is the impact of existing ground technologies on new vertiport facilities (e.g., 5G/6G)?
9. What requirements can be defined for UAM service approval/certification?
10. What is the feasibility of locating vertiports in densely populated areas with due consideration to safety, noise, access, fire codes, zoning requirements, multi-modal integration, etc.?

4.7 Security

Over the years, existing aviation systems have developed a high level of security, mainly because they have been self-contained [118]. The era of the Internet and interconnected systems brought a lot of disruption and security challenges [119–121]. That is particularly relevant to CNS [122]. Well-proven IT security technologies must be adopted, or new cybersecurity technologies must be developed to ensure secure UAM operations. That concerns airframe security, ground-to-air, air-to-air communications, and the entire range of anticipated systems and services envisioned in the UAM environment [14, 123–125]. The current focus is on adding IT security capabilities to the existing systems, while understanding the impact is insufficient. The IT security capabilities (such as firewalls and intrusion detection systems) often do not translate well to aviation systems, posing a significant threat to air operations in general and aircraft in particular [126]. Increasing threat levels of any kind requires establishing proactive governance measures and adopting a security culture [127]. That includes adhering to cybersecurity policies and best practices and training employees to be aware of security threats and able to apply proactive preventive and mitigation actions efficiently. Additionally, security assessments must be periodically repeated on the assets, processes, and playbooks, and new security measures must be tested to ensure continuous improvement [103, 107]. Furthermore, access controls should be used extensively to restrict access to data, critical infrastructure, and aircraft within the finely tuned clearance [126, 127]. Policies regarding security processes and locations for eVTOL users has been under discussion and development across the globe. Security screening will be needed for passengers if they are continuing on to traditional aviation through airports. For other passengers, moving from vertiport to vertiport, security screening is likely to be similar to general aviation or current helicopter operators.

4.7.1 State-of-the-art assessment

Aviation cybersecurity policies and standards are being developed on many forums, but a lack of coordination is leading to conflict and confusion. Certain attempts to coordinate are made, including by the ICAO with the Global Resilient Aviation Network (GRAN) Concept of Operations [128] and the International Aviation Trust Framework (IATF) [129]. Artificial intelligence, specifically machine learning, will play a crucial role in aviation cybersecurity [93]. A weaponized AI in the hands of cyber criminals poses a high risk but also highlights the opportunity for investing heavily in AI-enhanced defense and research [130]. Emerging machine learning models will enable greater protection against these sophisticated and complex threats [131]. Additionally, security encryption algorithms are already facing end-of-life due to quantum decryption techniques [132]. A good understanding of the vulnerability of current avionics systems to cybersecurity threats is missing. Cybersecurity is often an afterthought in development, which leads to insecure technologies and operational security gaps.

Risk assessment and management practices that focus on real-world safety hazards as they are impacted by cybersecurity are also limited. Strategies like micro-segmentation will be used to divide networks into multiple micro-segments and to apply separate access privileges. Micro-segmentation breaks data centers and cloud environments into segments down to the individual workload level. Organizations implement micro-segmentation to reduce the attack surface, achieve regulatory compliance, and contain breaches [133]. Work on big data and predictive analytics represent a promising domain for improving aviation security due to the evolution of aircraft sensors and processors which will provide large amounts of aviation data throughout the aviation ecosystem, including connectivity, operations, or predictive maintenance [95].

4.7.2 Gap analysis

Operational concepts must be developed to achieve operational integrity with cybersecurity at the outset [133]. Methodologies need to be developed and validated to translate IT cybersecurity capabilities into operational technology (OT) [134] of aviation cybersecurity operational concepts. Robust testing is necessary to assess the level of protection, such as penetration testing (or “red teaming”), where cyber experts try to gain access to the systems, and vulnerability testing to look for security flaws. Two conditions are necessary to allow the attacker to succeed in the vulnerability assessment and penetration testing (VAPT) [135]: 1) the existence of a vulnerability in the aviation system and 2) a pathway to attack that system or exploit that vulnerability. Furthermore,

aviation cybersecurity standards need to be developed and harmonized [136].

4.7.3 Open research areas

1. How may cyber security measures and considerations affect the development and utilization of AI-based aviation systems, e.g., those with high levels of automation?
2. Can emergent cybersecurity incidents be predicted and mitigated before having an adverse impact on the airspace system or individual aircraft?
3. Can airspace communications systems be matured to provide the capabilities of confidentiality, integrity, and availability per the operational need?
4. Can a quantum-resistant set of encryption algorithms be developed and implemented in time to avoid operational disruption?
5. Can the current public key infrastructure (PKI) IATF models be converted to quantum encryption or quantum decryption resistance?

4.8 Communications, navigation, and surveillance

The UAM aircraft are likely to operate in areas new to aviation. This will require infrastructure and performance standards for these operations and associated need for communication, navigation, and surveillance. Various solutions are considered for all these needs, but final performance requirements, particularly for AAM at scale, do not exist and remain an area of research.

Communication: A variety of communication options are being explored. These include aviation grade data communications, telemetry, downlink for sensor- or payload-collected data, pilot/controller voice, and non-nominal communications, and they are required at the entire operational volume and altitude. Therefore, they must be more reliable and secure than existing aviation solutions with service volumes that extend into urban environments [14, 41, 106, 137]. Implementations may include satellite communication (SATCOM), air-to-air (A2A) inter-aircraft and air-to-ground (A2G) communications, and a variety of wireless communication means designed for non-aviation actors [138, 139].

Navigation: Due to increased cybersecurity threats, challenging operational environments, expected higher volumes of operations, and increased reliance upon self-reported positional information, onboard navigation services for UAM operations must be reliable, ubiquitous, and more secure than traditional aviation navigation services [14, 41, 106, 107, 137]. One of the key technologies and standards

needed are for operations under GPS degraded or denied conditions.

Surveillance: Reliable surveillance technologies and standards are required to handle a high volume of UAM operations, recognize cooperative and non-cooperative aircraft and non-UAM objects, and achieve efficient tactical conflict prediction and resolution [6, 14, 123, 125]. Existing radar, RF, and triangulation-based technologies do not provide sufficient coverage and recognition level even though there are demonstrated advances in resolution when combined [85].

4.8.1 State-of-the-art assessment

Currently, there are no agreed-upon UAM CNS requirements, so it follows that there are no approved UAM CNS technologies or standards. Several candidate technologies exist at various levels of technical maturity and include the following:

- The UAS-specific C2 services (e.g., RTCA (Technical Committee for Aeronautics) DO-362 [140], Advanced Ultra Reliable Aviation (AURA) networks [141], e-conspicuity [142], remote ID [143];
- Commercial cellular, including the micro-operator concept [119, 144];
- Commercial satellite [139];
- Multiple satellite-based positioning, navigation, and timing (PNT) sources, including, but not limited to, global navigation satellite system (GNSS) services [125];
- Multiple ground-based PNT sources and landing-assist technologies [125];
- The A2A communications technologies for cooperative surveillance and swarm operations [138, 139];
- Low-power radar and radiometric tracking capabilities for non-cooperative surveillance [85, 125].

Most of these technologies were not originally intended for UAM operations, have legacy weaknesses (e.g., prone to interference), and were not designed to withstand negative external influences (e.g., spoofing and jamming) [85, 88, 123, 125, 127, 139, 144]. Therefore, further research, testing, and validation are required to determine their suitability or achieve higher maturity.

4.8.2 Gap analysis

The UAM CNS functional and performance requirements must be developed and agreed upon, followed by standards development and validation/certification procedures. These elements must be in place to determine if existing technologies and infrastructure are able to support UAM operations.

Testing should be done in the interim to accelerate technology development and to inform standards bodies. Known UAM CNS technology challenges include cybersecurity, spectrum availability, scalability, reliability/criticality, coverage in urban environments, and low-altitude surveillance [14, 88, 122, 123, 125–128, 133, 145].

One more technical gap is certifiability and integrity quantifiability of the advanced navigation algorithms and technologies, e.g., multisensor navigation including perception sensors, high accuracy carrier phase-based positioning, machine learning based methods, and the like, which might be necessary to fulfill the stringent UAM requirements [146]. A non-technical challenge in this design space is business viability [145]. In some world regions, UAM CNS services will likely be owned and operated by private industry, so profitability must be achieved while still allowing for sufficient regulatory oversight and reasonable affordability [14, 145].

4.8.3 Open research areas

1. What are the functional and performance requirements for UAM CNS Services?
2. To what extent can UAM utilize existing or planned consumer-oriented wireless communication technologies?
3. How can the responsibility be split for providing en route versus vertiport-proximity CNS services?
4. How does increased aircraft autonomy affect the criticality of CNS?
5. What is the required level of cybersecurity resilience for UAM CNS systems, and how can it be achieved?
6. What is the required level of external influence and environmental resilience for UAM CNS systems, and how can it be achieved?

4.9 Weather tolerance

UAM operations at low altitudes and in urban areas will be subject to micro-weather conditions that can change dynamically across smaller temporal and spatial scales and have higher levels of adversity along a flight path in comparison with traditional aviation. The unique weather patterns that affect UAM flights include strong wind-speed gradients, urban-updrafts/downdrafts, building wake shear, small-scale turbulence, urban vortex shedding, and localized icing phenomenon for cold climates. These weather patterns generated in low altitude and urban environments occur at smaller timescales than for global weather, which further challenges the technology required to mitigate effects of weather hazards on UAM. Changes needed in existing weather-related aviation technologies include advancement of stationary

weather sensing systems; on-board weather sensors and mitigation technologies; micro-weather forecasting systems to predict changes in weather within a timescale that relates to UAM; and novel decision support tools to optimize flight operations under weather uncertainties. Smaller and light-weight UAM aircraft are expected to be more sensitive to the micro-weather patterns, instigating better knowledge of the UAM limits for the range of weather characteristics and the development of novel weather detection and mitigation technologies. These advances will primarily enable safe UAM operations but also advance weather technologies for traditional aviation.

4.9.1 State-of-the-art assessment

Initial UAM commercial operations can be safely performed when long-lasting fair and low-wind weather is predicted; however, for adverse weather, operators are relying on airport weather reports and on-board aircraft stability sensors to assess safe operating conditions. Research has been conducted to evaluate the operational impacts and safety implications resulting from adverse weather conditions. The key weather-related safety considerations are collision and loss of power/control due to weather effects on aircraft stability, aerodynamic performance, energy consumption and on-board equipment functioning and lifetime [34]. Regional and local variations of urban weather and their impacts on UAM operations have been explored, such as the challenges associated with operations of UAS in harsh Nordic and Arctic conditions [147], highlighting the potential need for aircraft/system requirements that are tailored to the operating environment [148, 149]. Some development on the understanding of weather tolerance is underway for sUAS demonstrating the increased sensitivity to icing and complex airflow found at low altitudes [150–152]. On-board weather sensing and mitigation technologies such as ice detection and protection systems have been developed to reduce in-flight risks [153]. However, no standards for the certification of emerging ice protection/detection technologies exist. UAM/AAM operations will also require increased weather awareness at local scale. Possible approaches to improve weather forecasts and reduce uncertainties include smart urban sensing and the use of real-time crowdsourced weather data [154]. ASTM UAS weather standards and infrastructure for large-scale weather communication are in progress. While improving the accuracy of weather forecasts is a critical line of action, the ability to manage residual weather uncertainties is also key to delivering safe, efficient, and predictable flight paths. In this context, optimization approaches for UAM mission planning and traffic management have been explored to account for weather-related navigation uncertainties and deliver solutions that are robust to these

uncertainties [155]. One last research avenue concerns the weather impacts on ground infrastructure planning, design, and management. Airports or helipads can be adapted for the needs of UAM by adding deicing facilities and choosing touchdown and lift-off (TLOF) locations away from the wakes of structures. Vertiport standards to mitigate adverse weather effects caused by urban structures would include strategically and closely spaced weather stations that report at shorter intervals. Additionally, prevailing weather conditions should be considered to define vertiport design and location, allocation of final approach and take-off areas (FATOs), approach and departure path orientation, and operational procedures [149].

4.9.2 Gap analysis

Technical and design verification requirements and standards and operational practices to achieve and benchmark all-weather resilient UAS/eVTOL operations are yet to come. At a baseline level, definitions relative to weather and UAM (weather tolerance, gust/turbulence, flight stability) need to be universal for the growth of a unified industry. A universal vocabulary and technical definitions would promote consistency in global OEM standards for weather tolerance-related technologies and flight stability criteria, which do not exist at present. A deeper understanding of urban weather impacts on UAM aircraft performance is needed for the specification of aircraft requirements. Both the technological advancement in weather sensing systems at ground/vertiport stations and on-board sensors and the development of viable business cases that provide return on investments will be required to obtain weather observations and relay information at a faster rate than what currently exists for traditional aviation. Observational data has not been available to validate weather models or forecasts, which are generated through utilization of these models.

4.9.3 Open research areas

1. How do low-altitude atmospheric turbulence levels and urban airflows affect UAM aircraft stability and energy consumption?
2. Will the range in UAM aircraft configurations challenge a universal understanding of weather tolerance, or can knowledge be transferred between configurations and sizes?
3. What are effective and durable UAM-scale icephobic coatings, ice protection and deicing systems, and ice detection sensors?
4. Will extreme hot weather events require cooling systems to mitigate battery or other system failures?

5. What on-board technologies can be used to measure the impacts of adverse weather conditions on aircraft components and provide mitigations?
6. How do on-board technologies for weather detection and avoidance affect the overall aircraft performance?
7. How should UAM flight planning and traffic management solutions account for and manage weather-related uncertainties?
8. Can weather sensing or prediction technology be adapted to the timescale and nowcasting required for UAM?
9. How can the quality, costs and latency of urban weather information be improved?
10. Can static or semi-static equivalency testing be a cost effective and reliable method to evaluate UAM for assessment of weather tolerance?
11. How does micro-weather effect the design and configuration of vertiports and the applicable approach and departure procedures?

5 Operation

The adoption of UAM will depend on the technological advances discussed in the previous section, but they will not be sufficient for the adoption and integration of the new mobility. Operational aspects, including environmental impact (emissions and noise), maintenance, safety, security, intersection with infrastructure, and data protection need to be considered. This section provides an overview of each operational aspect, discusses the current state of the art, and identifies open research questions based on gap analysis conducted. Assuring sustainable operations in the UAM domain will be a prerequisite for the social acceptance as discussed in Sect. 6 later.

5.1 Environmental emissions

The UAM industry can be a leader in the aviation transition towards net-zero greenhouse gas (GHG) emissions [156]. Several industry front runners are using fully electric aircraft designs with zero “tailpipe” emissions, however, the lifecycle emissions (e.g., from battery production, charging from an electrical grid, etc.) must be considered when considering the overall environmental impact [157, 158]. Options also exist for propulsion systems that use hydrogen (through fuel cells or direct combustion) or sustainable aviation fuels (e.g., hybrid-electric engines), which potentially increases the range of the aircraft. Although fully battery-electric aircraft will produce no CO₂ (or other) emissions, the lifecycle emissions need to be considered as the battery can represent a large portion of the overall

lifecycle emissions of the operating life of the aircraft. For example, frequent replacements of the aircraft battery pack could have greater lifecycle emissions than using an engine with conventional fuel. Similarly, fuel production emissions are highly dependent on the method used by local grids to generate their electricity (for battery charging), or the method used to generate H₂ or SAF. Additionally, novel technologies under development for UAM, including those used for air quality and emissions monitoring, have the potential to positively influence other transportation sectors. UAM systems, particularly eVTOL aircraft, however, tend to have significantly higher energy demand per passenger-kilometer compared to competing ground-based modes of transport. When comparing the energy consumption and resulting CO₂ emissions of eVTOLs with other transportation modes, eVTOLs are expected to produce less CO₂ than conventional helicopters in urban or regional transportation but consume more energy than electrically driven ground transportation options such as electric cars [61].

5.1.1 State-of-the-art assessment

Current emissions standards (ICAO Annex 16 Vol II) are only applicable to larger aircraft powered by turbojet/turbofan engines (>26.7 kN-thrust); therefore, the current size of UAM would not be regulated by these standards. The UAM fleet could be considered analogous to the current general aviation fleet, which represents only about 1 percent of total emissions from the aviation sector [159]; however, depending on how the UAM sector grows, it could start to represent a larger proportion of emissions from the aviation sector [9]. Furthermore, emissions standards currently only focus on exhaust emissions, and as mentioned in the “Overview” section, the lifecycle emissions may be a more important consideration for the UAM sector. It would need to be determined whether these emissions from energy production should be book-kept as aviation industry specific or come from other industries. Also, a standardized methodology would be needed for the lifecycle analysis so that consistent reporting occurs (like what ICAO had developed for SAF). Finally, the UAM propulsion technologies are predicted to eventually scale up to larger aircraft (>26.7 kN-thrust), so it is relevant to start considering these factors today.

5.1.2 Gap analysis

Current studies comparing the environmental footprint of UAM to other modes of transport (such as ground electric) show that the results are highly dependent on assumptions made by the authors (e.g., there are large impacts on the assessments depending on the assumed electrical grid carbon intensity as well as passenger load). For example, some

studies show UAM has nearly twice the carbon footprint over ground electric transport while others show as low as a 6-percent difference in emissions between the two modes. As technological improvements in both UAM and ground transportation occur, continual updates to emissions studies are needed for fair comparison. To enable the reuse or recycling of electric batteries, multiple barriers must be addressed including the high costs and lack of clear standards and regulations for the classification, storage, handling, and processing of batteries, enabling predictable end-of-use conditions. Additionally, although the smaller aircraft suitable for UAM do not have emissions requirements, the emissions of large fleets of aircraft must be considered.

5.1.3 Open research areas

1. A standardized methodology for lifecycle analysis is needed; will the aviation sector track emissions due to fuel and electric production?
2. Does integrating UAM into a holistic transportation system contribute to overall lower emissions for the transportation sector? Is there an optimized way for the system to be used?

5.2 Environmental noise

Currently, UAM/AAM has a wide range of noise source characteristics due to different fuselage designs, propulsion configurations, size, maximum take-off mass, and flight modes. Characterizing noise in a standardized way is challenging but will be key to ensuring sustainable operations [160, 161] as outlined by various regulatory entities worldwide [17, 162]. In urban areas, noise due to UAM operations will need assessments to account for:

- Noise that adds to current noise such as noise generated by urban transportation.
- High operational tempo near vertiports [163].
- Optimizing routes and operating profiles to minimize noise, and account for environmental influences such as population density, reflections, and scattering from buildings [48].

Beyond the sources, acoustic propagation in an urban environment requires considerations such as multiple reflections, diffractions, and masking effects, which will strongly modify the noise perceived by the citizens. In rural areas, UAM/AAM should be optimized to minimize interference with the natural environment. Electric propulsion and low-noise specifications are helpful for this requirement,

however further considerations should be the subject of appropriate analysis.

5.2.1 State-of-the-art assessment

Currently, the regulatory environment ranges between insufficient and sufficient but not optimized. Action is needed to adapt existing regulations to new aircraft configurations. Current FAA interim noise certification of UAS is on a case-by-case basis using rules of particular applicability (RPA) [164]. General rules on UAS noise certification remain and continue to be developed. A multitude of noise mitigation techniques have been developed over the years that can be applied, but there are new techniques for noise reduction that are enabled by the UAM/AAM multi-rotor, alternative propulsion configurations (e.g., rotor phase-locking), while other techniques are not suitable due to the unique configurations of UAM/AAM. For decades, simulation tools have been developed to estimate the noise radiated by helicopters and propellers. Ranging from low-order models to high-fidelity methods, these tools can be applied and modified for UAM/AAM applications [165]. Urban acoustic propagation tools have been developed for many years to evaluate the noise generated by ground vehicles (cars, motorbikes, bus, trains, etc.). As these sources are on the ground, propagation tools often use a 2.5D ray-tracing method, which is not adequate for sources moving at altitudes higher than buildings.

5.2.2 Gap analysis

The noise generation of AAM aircraft differs from conventional rotorcraft and is not currently well understood. As a result, new standards and measurement techniques need to be established. Current ICAO standard (for helicopters) is a single-point measurement with no correction for human perception. Additionally, further research into multidisciplinary optimization of UAM/AAM specific propulsion systems for noise and thrust is needed. Viability of current noise simulation tools for smaller rotating parts, particularly around determining effects of scaling, requires further investigation. Furthermore, it is unclear how radiation mechanisms must be modified when switching from rotors supporting blades several meters long to rotors potentially as short as a few centimeters. Assessment methods focused on the transition envelope, and those that include propulsor-airframe and propulsor-propulsor interaction noise, acoustic sensitivity to atmospheric turbulence, and noise scattering need to be developed to adequately capture operations.

5.2.3 Open research areas

1. How can planners take advantage of ambient noise levels to mask the detectability of UAM operations?
2. How can existing urban propagation tools be applied to flying acoustic sources?
3. How can acoustic prediction tools be improved to assess the noise of arbitrary AAM aircraft configurations?

5.3 Maintenance

Integrating UAM concepts into an industry renowned for being the safest mode of transportation for decades demands the continuation and improvement of that reputation. This improvement must be achieved with maintenance practices consistent with those already established that have produced desirable results. Introduction of UAM aircraft will bring technologies that pose challenges to existing maintenance practices. Namely, the use of hydrogen power systems, electric power components, and altering the application of traditional materials or aircraft components will elicit challenges to the aviation industry. Infrastructure does not yet exist for widespread, long-term maintenance of electric or hydrogen-powered propulsion systems. Additionally, aircraft maintenance service providers are not yet equipped with the knowledge, staff, or tools to operate UAM technology on even a small scale, nor has the aviation industry developed standards for technologies unique to UAM function [166].

As these operations will occur at local level, the maintenance infrastructure to support routine or preventive maintenance is key for sustainment. Therefore, qualified maintenance capabilities, personnel, and parts supply chain need to be established by each operator. In addition, curriculum and training programs for high voltage aircraft maintenance need to be established to prepare a qualified workforce to support the needs [167].

5.3.1 State-of-the-art assessment

Operational differences that may elicit maintenance adaptations are mostly related to shorter service routes and areas. The idea of on-demand or ride-sharing aircraft means an increase in the number of take-off and landing cycles, less predictable operation and maintenance planning, more variation of engine speeds (resulting from less time spent at a cruise altitude), and vibration profiles that accompany such changes. All these factors will potentially affect the inspection cycle of components and airframes that could produce a more frequent need for repairs, component exchanges, and scheduled maintenance intervals. Demonstration of new technologies will have a noticeable impact on maintenance

practices that may even affect the distribution of service centers based on the smaller scale urban operational areas [168]. Coupled with a need for infrastructure growth to support UAM aircraft maintenance, namely with new types of power plants, there may also be a need for specialized maintenance or servicing facilities that do not yet exist.

5.3.2 Gap analysis

Generally, standards for UAM aircraft, materials, propulsion systems, and maintenance practices are lacking. The FAA does not have any regulations specific to UAM at all while the EASA does have a framework of high-level directives aimed at the establishment of UAM maintenance standards (EASA SC-VTOL-01). One exception is the existence and ongoing development of standards for additive manufacturing (three-dimensional (3D) printing), by the Society of Automotive Engineers (SAE). The SAE has published standards for fused-filament (nonmetallic) processes and fabrication as well as several metal alloys including titanium, nickel, steel, stainless steel, and aluminum. Similarly, process standards for additive manufacturing of these metals have also been published. Certified maintenance is needed for operations such as passenger transportation and development of necessary maintenance certifications for UAM lag behind pilot certifications. Curriculum for technicians and training programs need to be developed to support the growing needs of technicians. Furthermore, parts standardization (to the extent possible) needs to be explored to reduce the total maintenance, repair, and overhaul costs and time.

5.3.3 Open research areas

1. An area often overlooked is maintenance personnel training, education, and certification. With more widespread use of additive manufacturing, will new repair methods and fatigue properties (also known through study and testing to inform of servicing intervals) be necessary?
2. What maintenance training, curriculum, and procedures need to be established to ensure that these practices are followed at local levels?
3. What safety practices are needed for new technologies?
4. What infrastructure changes are needed to ensure appropriate repair facilities for new technologies and established supply services?
5. What methods for determining aircraft health status and data-driven prognostics in real-time with trend analyses are needed?

6. Should assessment of where maintenance procedures and parts (e.g., charging nozzles) be standardized across the industry to reduce cost and repair time?
7. How can artificial-intelligence-based predictive maintenance solutions be applied for UAM?

5.4 Safety and security from the operational perspective

Safety is the most important facet of UAM operations. To sustain safety for UAM operational areas, various aspects such as certification; training; operations; system performance; UTM; infrastructure; SMS (addressed in IFAR UAM WG Tech Area 5); security; and others (such as human and organizational factors or ecological aspects) must be considered. UAM aircraft and operational support systems, which are forecasted to operate under highly autonomous paradigms, will require new and modified certification techniques including the development of safety assurance arguments for machine learning/artificial intelligence utilized in their components and systems [169]. The UAM operators and other stakeholders involved in UAM operations (e.g., vertiport operations staff) need appropriate training to reflect unique operational needs such as communication in emergencies, avoidance of (or flight in) adverse weather, contingency management, and system degradation. Additionally, operational considerations such as airspace type; environment (area size and density, time of day); transport type (cargo, air taxi, commercial/non); system tools (decision support, communication systems, SMS, sequencing, information sharing and data management); and roles (ATC, pilot, crew, airlines) must be taken into consideration. System performance considerations include initial and continuous airworthiness assessments, accident and incident investigation, manufacturing quality control, regulations, guidelines, practices, and operational procedures for safety-critical situations with human-automated system interactions [170].

5.4.1 State-of-the-art assessment

Currently, there is no accepted criteria for assuring the safety of UAM operations. Part of the SORA (specific operations risk assessment) methodology, targeting drone operations and air mobility, and five specific assurance and integrity level (SAIL) categories, i.e., SAIL I, II, III, IV, V, and VI, have been developed, and they indicate the level of risk and required level of safety an authority is willing to accept. ICAO has formed an Advanced Air Mobility Study Group to support safe, secure, efficient, and sustainable integration of UAM/AAM operations [171]. When defining safety standards and regulations for this domain, local

considerations are most relevant, including the current regulatory environment, impacted aircraft resources, and other local safety considerations. However, there are many common issues when operating in similar urban environments. The FAA in the United States and EASA in Europe have safety management regulations applicable to Part 135 (helicopter) operations and UAS operations, respectively. Some of these regulations are transferable (and applicable) to UAM for many urban areas, but specific UAM safety regulations will need to be tailored for more frequent operations and/or unique urban missions. Though Part 135 regulations may be used as a starting point, UAM safety regulations will need to adjust over time as UAM operations become more mainstream and the airspace becomes more densely populated. Criteria for certification with increased autonomy and various emerging technologies in mind are needed.

5.4.2 Gap analysis

Safety guidelines and regulations for helicopters, general aviation, and automobiles currently exist, but they are not all transferable or relevant to UAM operations. These guidelines include performance standards like navigation, separation, communication, and external services; vertiport standards like security, passenger and cargo transfer, weather challenges and protocol; supporting systems standards like decision support, situational awareness, communication protocols, and simulation training tools; and mixed-use standards like tactical separation, contingency operations management, crashworthiness analysis, and urban traffic simulation systems. Standardizing interfaces to allow communication and navigation systems to be used across different operation types will also be important. Autonomous and highly automated aircraft can pose a different set of safety risks during operations that need to be clarified and addressed [172]. Addressing these risks is important in demonstrating to authorities that proposed UAM operations are safe.

5.4.3 Open research areas

1. How can external factors (weather, environment, air-flow, altitude, ground population, and airspace density) be modeled and corresponding safety impacts predicted?
2. How can safety assurance be tested and subsequently demonstrated to authorities? What criteria/metrics and thresholds determine safe operations? What is an adequate/acceptable level of safety?
3. How can nondeterministic AI-based systems be verified and validated from the safety perspective?

4. What resources and technology developments will be needed for ATM to handle a large volume and diversity of aircraft with different needs (minimum separation between aircraft, proximity to terrain, autonomous system reporting, etc.)?
5. What data sources and safety assessments can be conducted predictively during flights, and between flights?
6. What aircraft capabilities are needed, particularly those that may involve increased use of automation?

5.5 Intersection with infrastructure

In the near term at low-operational tempo, the UAM/AAM environment will likely support operations with existing infrastructure. As operational tempo increases, however, current infrastructure solutions are unlikely to be suitable to meet the demand. To support the ability to safely scale, integration with new technology and infrastructure is likely a necessity. Examples of this are additional systems deployed to support CNSI in a city. Local and distributed weather sensors for predictive capabilities will be needed. The integration of airspace management and air traffic control systems will also be necessary; however, as the associated technologies and infrastructure changes are identified, a greater understanding of the proposed changes and their impacts will be necessary prior to implementation. Potential impacts may be on local infrastructure such as the electrical grid for facilities providing recharging services. Similarly, alternative fuels may be required which will result in special handling and storage requirements and an understanding of the potential environmental and health impacts. Public safety and security needs also warrant consideration in not only leveraging vertiports for response efforts but also the ability to respond to incidents at the facility [173]. Community equity considerations for vertiport placement and the needs of the community are to be considered as well as how operations integrate with intermodal transportation beyond the local facility.

5.5.1 State-of-the-art assessment

Vertiports share some similarities with heliports that enabled the initial leveraging of ICAO Annex 14 Volume 2, which defines the characteristics and limitations of a heliport or similar facility along with the provided services. Using heliports for initial inspiration provided insight into initial conceptual designs of vertiports that included elements related to the necessary markings, lighting, and the definition and dimensions of the TLOF area and final approach and take-off (FATO) areas. Also, numerous organizational and operational considerations are common to both vertiports and heliports such as safety management and planned flight

trajectories with respect to airspace integration [173]. Nevertheless, as the flight characteristics and reliability of eVTOL aircraft are different to conventional helicopters, most heliport requirements should be adapted using a safety-based approach and consider the impact on local specificities. More recently, the FAA has published its Engineering Brief No. 105 on Vertiport Design [169], and the ASTM standards working group published its New Specification for Vertiport Design. The Civil Aviation Safety Authority (CASA) and EASA have also published vertiport design guidelines [173, 174]. These publications have provided further guidance on specifications for vertiport infrastructure that serves to refine the considerations and guidance; however, design is but one narrow, albeit important, aspect related to the introduction of vertiports into communities and the intersection with infrastructure. Work is underway to better understand and account for the many other elements and factors related to the establishment of vertiport facilities and accommodation of the operations that will follow.

5.5.2 Gap analysis

There are open questions on what technology is required at the vertiport to support the safe movement of aircraft and what types of services can be or need to be routinely provided or available on demand. Additionally, vertiports will likely be in a variety of traditional and nontraditional places (e.g., floating on water, rooftops) and may use different and new types of construction materials. The relationships of these materials and their ability to support high operational tempos of evolving aircraft will need to be understood. Additionally, different aircraft fuel sources will have design and operational impacts (e.g., scheduling recharging) and the environmental impact to the community will need to be considered. These issues also play a role in assessing the impact of vertiports on equity and socioeconomic issues to the local population. Understanding how the vertiports integrate to the overall transportation infrastructure of a city or broader community is also in the early stages and in need of further research [175].

It is also possible that some vertiports will be located at airports based on operator business cases. Such co-location may require additional understanding of wake vortex susceptibility and interactions with other air traffic. Furthermore, zoning regulations, fire codes, typical winds/weather, access and security considerations, passenger convenience, and future construction plans need to be considered while determining location of vertiports. Communities will particularly be interested in noise and ground traffic that vertiports and operations nearby may generate [176].

5.5.3 Open research areas

1. How can the introduction of vertiports minimize community/environmental impact while maximizing benefit?
2. What are the CNSI and supporting service requirements associated with vertiports?
3. What are the public safety and security needs with respect to vertiports and the associated operations?
4. What are the key factors related to vertiport introduction in a community and public acceptance?
5. How do city and urban planners incorporate vertiports into their processes and considerations?
6. How will vertiports integrate into the overall transportation infrastructure of a city or broader community?
7. What are the resource requirements to support the integration of vertiports into city infrastructure?
8. How modular and flexible do vertiports need to be designed to address changing external requirements (e.g. demand, weather)

5.6 Data protection and security

Data security is a relatively mature focus of physical and IT security and is built on well-proven protection measures and technologies. System security engineering practices are used to match protection needs (PN) against the data classification based on regulatory, organizational, or other requirements [177]. The security requirements are set for the system containing, controlling, or accessing the data depending on the sensitivity level [123]. The technologies used for IT security range from network security capabilities such as firewalls and intrusion detection systems to localized data protection technologies that rely on encryption, user/component identification, and various monitoring capabilities [128].

Operational technologies (OT) [134], as opposed to IT, are generally defined as those digital technologies that affect the physical world. This domain includes flight management systems, engine controls, air traffic control systems, and many others [90]. Whether that is managing flight trajectories, aircraft safety, or other systems that can cause physical effects, data security in this OT domain is not well defined [128] and, in many cases, is fundamentally nonexistent [127].

5.6.1 State-of-the-art assessment

Data security in the OT environment, particularly UTM environments, is not sufficiently addressed, even though some aspects of UTM have been addressed well [124].

Security within UTM functional architecture is based on IT security network concepts and addresses data security in the control plane of UTM [124]. By design, it does not, however, manage the data security of the overall UTM/UAM environment and cannot attribute behaviors to all users or systems. Therefore, it cannot identify the full range of possible attempts to compromise data or operations that depend on sensitive data.

Much of the current attempt at data security is focused on translating IT security concepts to the OT environment. However, this approach has not been successful [126]. Aside from the OT interactions with the physical world, the OT environment is also not an “always connected” environment like IT. It comprises various operations and technologies that do not map well to IT technologies and concepts. Generally, attempts to convert or translate IT concepts such as firewalls or intrusion detection and prevention systems brought poor results as these types of security controls and encryption are used for IT security data protection [126].

5.6.2 Gap analysis

The current differences between the IT and aviation OT security industries are numerous. The identification of users, processes, and system components leads the list [128]. Identifying the actor in data security and associating appropriate accesses and actions is critical. The technologies needed to affect these capabilities may differ significantly from those used in IT. Providing protection needs in an environment that is not always connected is problematic [128]. On the other hand, digital transformation and increased levels of integration and connectivity open new threats to data, while limited public information on data breaches limits the development of dedicated data protection solutions [133].

5.6.3 Open research areas

1. What capabilities, concepts, or technologies are needed to ensure UAM/AAM data security? How are users, systems, software, and other processes uniquely identified, and how is access provided in the UAS/UTM industrial environment?
2. Can the IT concepts and capabilities, such as firewall or intrusion detection, be applied to the UAM/AAM environment, or do we need new designs?
3. How do we measure the effectiveness of IT technological approaches in the UAS/UTM environment?
4. What capabilities, concepts, or technologies are needed to affect UAS/UTM industry data security?
5. How do we integrate these developments with the ICAO IAFT and GRAN Concept of Operations?

6 Social acceptance

For UAM to be successfully integrated into the market as an additional mobility service, acceptance and willingness to use it among the population are key prerequisites. Various studies indicate that there is still room for improvement regarding willingness to use. For instance, Al Haddad et al. found that only 36% of respondents could imagine using drones as a means of transportation within the next two years [178], whereas Ferreira & Kalakou reported a much higher intention to use at 70% [179]. Adoption readiness also varies considerably across countries. Yedavalli & Mooberry examined readiness in four nations, showing the highest level in Mexico City (33%), followed by Los Angeles (23%), Switzerland (15%), and New Zealand (12%) [180].

To increase adoption readiness, it is essential to understand which factors determine acceptance and, consequently, adoption. Several studies identified safety concerns as a major barrier [178, 181–185]. Key risk concerns include accidents, crashes, cybersecurity, and privacy issues [178, 185, 186]. Conversely, high perceived safety positively influences trust, which in turn mediates behavioral intention [187]. Several studies on UAM acceptance are grounded in the Technology Acceptance Model (TAM) originally developed by Davis [188]. These studies confirm that the model applies to UAM and show that perceived usefulness and perceived ease of use strongly predict attitudes and behavioral intentions toward UAM. Moreover, trust consistently emerges as the most influential predictor of usage intention [189, 190]. In particular, initial trust is the strongest predictor of user attitude toward UAM. Strong technology beliefs enhance trust and mitigate perceived risks [189].

Research also shows that acceptance differs across socio-demographic groups. Willingness to use UAM increases with higher income and education [179, 191]. Women tend to show greater safety and security concerns than men [179, 192]. Some studies have also identified distinct user segments. For instance, Lotz et al. describe three types of users: automation-skeptical, environmentally conscious, and cost-conscious [192]. Al Haddad et al. additionally found that cultural background and automation affinity influence user segmentation [178].

A key barrier to UAM adoption could be its price level, as services are likely to be accessible only to affluent groups initially due to high costs resulting from investment and supply constraints [191]. This raises questions of social equity and fair access. Several studies have examined price sensitivity and willingness to pay. Alongside safety, trip duration, and service quality, price is a crucial determinant of acceptance [178, 193] and is highlighted as a critical factor in further demand studies [194–197]. Analyses show that most users are unwilling to pay more than standard taxi fares; in

some studies, the average willingness to pay is even lower [198, 199]. According to Asmer et al., demand drops significantly when prices exceed €2.50 per kilometer, regardless of vertiport density [197]. Thus, aligning UAM prices with regular taxi fares or even lower substantially promotes adoption [178].

Since UAM services have not yet been implemented, people lack real-life passenger experience. Consequently, much of the research relies on surveys and hypothetical scenarios. This limited experience restricts realism, and respondents may still perceive UAM as speculative [189]. However, some studies have attempted to make UAM experiences more tangible through virtual reality (VR) and simulators [200, 201]. A simulator experiment by Papenfuß et al. shows that simulated flight experiences can increase perceived usefulness and foster positive attitudes [200]. Moreover, gaining experience with air taxis can reduce concerns and enhance trust and willingness to use [179, 200].

Existing research provides initial insights into the acceptance and willingness to use UAM. It is evident that initial trust plays a central role and should be encouraged. Acceptance and adoption depend on how effectively safety and privacy concerns are addressed [186]. A practical implication is to communicate transparently about safety protocols, data protection, and security to strengthen public trust [181]. Furthermore, due to potentially high travel costs that may exacerbate inequality, policymakers should ensure affordability and prevent exclusion of broader population groups [191]. For future research, more studies could use VR and simulators to enhance realism. Additionally, further research should explore what types of information and in-flight communication can increase passengers' confidence in air taxis. Studies on autonomous transportation have shown that user-centered HMI design is crucial, as it shapes early user attitudes and affects ease of use, trust, and perceived safety [202]. Future work could also investigate design requirements for different user groups.

User acceptance testing as described above is typically conducted in the development of a new product or technology. On the other hand, the concept of societal acceptance is broader and defined as “a process of learning about, accepting, and adapting to an innovation” [203]. It needs to be carefully evaluated for UAM (including autonomous aircraft) as most people are unfamiliar with UAM and its significant impacts on the human (e.g., safety, noise, visual clutter, privacy, development patterns, etc.) and natural environments. For communities that choose to adopt and integrate UAM into local transportation systems, the introduction and growth of UAM should be carefully discussed, assessed, and managed to ensure equity and sustainable improvement with regards to quality of life. Societal acceptance is crucial for the implementation of UAM [204] and a

lack of profitability and societal acceptance were the driving factors why initial UAM concepts of the last century failed [205]. A recent review of public acceptance studies concludes that increased awareness or adoption of advanced aviation technologies leads to higher acceptance [206]. The following sections will highlight state-of-the-art, gaps and open research questions related to societal acceptance covering the areas of autonomy, environmental concerns (emissions and noise), and perceived safety.

6.1 Autonomy and the societal perspective

Aircraft autonomy implies a transition from having human experts (a.k.a. pilots) onboard and responsible for – and directly impacted by – flight safety to new modes of operation. Possible solutions can be “simplified on-board pilot” or “multi-aircraft remote supervision”. For these modes of operation, safety by design must be implemented in automation agents. Moreover, the assurance of air traffic safety and broader airspace management would be increasingly automated. This proposed transition needs to be carefully analyzed and managed as the process entails significant technical challenges and risks. These are combined with potentially foundational societal changes concerning safety (real and perceived); responsibility; accountability; and liability. These issues are likely to be raised across other forms of transportation as well.

6.1.1 State-of-the-art assessment

Public surveys have been conducted about UAM societal acceptance for various regions around the world [207–212]. However, they might potentially be influenced by organizational biases or domain knowledge, e.g. surveys conducted by aeronautics organizations or industries, or surveys limited to favorable categories of participants (those in higher income brackets).

As far as autonomy and UAM is concerned, works about so-called autonomous cars [213] are likely to provide relevant early insights. A pertinent observation from these studies is that the technical word autonomy is ambiguous for most non-roboticists and may result in misunderstandings and/or unfounded expectations. Assessments of the potential reaction and/or acceptance of increasing autonomy should clearly present which functions are actually automated; reasons why the automation is expected to be beneficial; and relevant limitations. Furthermore, it should provide descriptions of human and automation authorities in potentially critical or uncertain situations and their responsibility in decision-making.

The perceived risk, excitement and innovation are the primary components of future users’ attitude towards

pilotless aircraft and should be addressed in communicating about UAM [214]. Current user acceptance studies on autonomous flying are relying on simulated flights and have shown that passengers want to be informed about the intentions of the autonomous aircraft [215]. As increasingly automated systems are introduced, accidents due to automation (e.g., self-driving cars) and those that humans could have probably mitigated are likely to cause disproportionate societal reactions, even if the overall level of safety is improved [216]. To offset this tendency, it is likely that automated systems will need to contribute to safety levels significantly better than nonautomated systems.

Mitigation strategies for improving the societal acceptance of UAM are proposed in [209]. Here, actions in categories such as regulation operation, human response, and tools/technologies are discussed.

6.1.2 Gap analysis

Along with assessing the question of increasing “autonomy” of UAM operations, the relevance of UAM itself and of the possible societal effects (beneficial and adverse) should be assessed. For example, is UAM anticipated to fill gaps in the market (if so, which gaps) or solve issues in urban mobility (if so, which issues, and could they be solved differently)? What is the equity of UAM across a given society and territory? Is it sustainable and how is it likely to influence future development? How should related applications of “autonomous” aircraft be considered (e.g., outside cities for food or first aid supply to remote communities, islands, disaster areas)? In a more general sense, the global question of mobility as it relates to work, facilities, and leisure should be evaluated. Moreover, there are still many uncertainties related to UAM with regards to safety, cost, time saved in addition to its impacts on people, installations and environment including any rebound effects. Relative to “autonomy,” the technical difficulties/benefits ratio should be carefully assessed within appropriate regulatory and oversight frameworks.

6.1.3 Open research areas

1. What are the motivations and needs of UAM and how to conduct realistic simulations, experiments, and pilot deployments to assess whether they are likely to be fulfilled?
2. How to facilitate open public discussions on UAM?
3. How to conduct a comprehensive environmental assessment of UAM taking into account the aircraft and the physical and digital infrastructures?

4. How to assess the equity of UAM regarding all societal components and all territories?
5. How to address user acceptance, especially in the interaction with the aircraft when no pilot is on board?

6.2 Environmental emissions and the societal perspective

The aviation sector is already drawing increased public scrutiny over environmental concerns. These concerns have manifested in:

1. Public opposition to new airports or expansions due to concerns regarding local air quality and noise (e.g., the London Heathrow Airport Expansion court challenge).
2. Local bans on specific fuels due to environmental/health concerns (e.g., 100LL aviation gasoline—banned at two airports in California, U.S.A.).
3. Opposition to bio-derived fuels over concerns about land-use.

The UAM sector needs to be cognizant of these societal concerns if the fleet size grows substantially. Although UAM may currently be using battery-electric propulsion systems, other engines such as hydrogen and/or SAF hybrid-electric may also become prevalent. For example, if SAF is used as a fuel (in turbine or compression ignition engines), there could be public acceptance issues in the future, despite its potentially low lifecycle emissions, if it is the only sector in urban areas producing emissions. Also, if the UAM fleet is large, NO_x (smog) and odor from emissions could be an issue (smaller engines tend to have lower combustion efficiencies and therefore more odor).

6.2.1 State-of-the-art assessment

Since the 1970s, ICAO has developed emissions standards (Annex 16, Vol II) to reduce the impact of aviation on local air quality in the vicinity of airports. These standards do not apply to the class of aircraft that are being developed for the UAM sector; however, from a societal acceptance standpoint, as other urban transportation modes (buses and cars) are rapidly electrifying, any local emissions that the UAM aircraft produce may be subject to increased scrutiny. Also, UAM may have a more widespread operating footprint and be more visible to the public (e.g., many vertiports spread throughout a city vs. single local airports). Research on the environmental impact of UAM has focused on life-cycle analysis that spans energy generation, aircraft material production and flight operations. Some studies have delved into electricity-related emissions, given the mainstream electric propulsion UAM aircraft concept. A region's grid

carbon intensity and the type of power generation structure were found to be crucial factors, emphasizing the influence of the operations location on UAM environmental impact [156, 217, 218]. Another area of investigation concerns the material sourcing and production for UAM aircraft assembly. Carbon fiber has been identified as a significant contributor to production-related emissions as it accounts for a significant part of UAM aircraft material composition in most designs [219]. Propulsion system materials, such as hydrogen fuel cell components, can also be a major contributor to production emissions [220]. The environmental impact of UAM is also highly influenced by operational factors such as mission profiles and aircraft load factor. Closer adherence to design ranges, higher passenger capacity with autonomous piloting and longer trips have been found to improve sustainability [219, 221]. Comparative analyses with other transportation modes indicate that, in certain scenarios, UAM aircraft, especially eVTOL models, exhibit lower greenhouse gas emissions compared to internal combustion ground vehicles and are competitive with public transport [156, 219]. However, challenges exist, particularly for short-distance trips and certain rotor configurations.

6.2.2 Gap analysis

As there are many unknowns about how operations for the UAM sector will actually emerge (e.g., vertiports throughout urban areas, size of the fleet, propulsion technology, etc.), it will be difficult to predict local UAM emissions and societal acceptance of UAM. Despite recent progress in understanding the environmental impact of UAM operations, there are several areas for further investigation, including the influence of regional characteristics (e.g., regarding electricity generation sources, overall transportation ecosystem) on UAM environmental footprint, the optimization of UAM aircraft design and flight operations in light of environmental performance goals, and the impacts of adopting hybrid configurations and alternative fuels. Additionally, public perception issues surrounding some fuels, such as land-use concerns with bio-derived fuels or safety issues with hydrogen, use may require public education to alleviate these concerns.

6.2.3 Open research areas

1. What will society accept in an urban environment for UAM emissions?
2. What does society accept for a “fuel” (hydrogen, SAF, batteries)?

6.3 Environmental noise and the societal perspective

With the introduction of UAM aircraft flying in airspace away from airports where people are not accustomed to flight operations, there is a possibility of public concern related to safety, noise, privacy, and visual pollution [34]. In most representative studies regarding community attitude towards emerging operations such as drones, the response has been found to be slightly more positive than negative. The opinions are based on numerous complexities such as gender and age but also on the individual's level of information and experience about drones [222, 223]. Opinions also differ depending on the use application, with rescue and public safety being the applications with the highest acceptance levels. Moreover, among all concerns about the usage of drones, noise concerns were found to have the strongest impact on acceptance [222]. Noise is one of the main obstacles for UAM deployment and acceptance challenges are expected for "nonurgent" usage (non-lifesaving). It is crucial to understand human responses to UAM noise and develop metrics and models to evaluate and predict such responses in order to guide UAM stakeholders towards making aircraft design decisions, incorporating technologies, placing infrastructure and establishing operational procedures that increase the probability of UAM operations being well-received by the general public.

6.3.1 State-of-the-art assessment

UAM aircraft noise (as it concerns people on the ground, not people in the aircraft itself) is somewhat unique given the variability of noise sources from distinct aircraft design and the expected volume of operations over densely populated areas where no other significant noise sources fly over. Tens of millions of people are affected by aircraft noise in the current air transportation system. To quantify this level of exposure, noise metrics have evolved over time as a result of knowledge gained about human response to noise, measurement and data processing capabilities, metrics usage and interpretation [11]. Current metrics for aircraft design focus on noise certification, including A-weighted sound pressure level (L_{Amax}), A-weighted sound exposure level (L_{AE}), and effective perceived noise level (EPNL). Community noise metrics involve integrated noise exposure measures such as day-night average sound level (DNL) and community noise equivalent level (CNEL) and are typically used for the purpose of land use planning. A particular challenge for UAM noise assessment is the variability in acoustic effects of various aircraft designs, which might compromise the effectiveness of standard noise metrics to compare their acoustic impacts. Integration of multiple aeroacoustic

metrics has been explored for UAM aircraft noise prediction [224]. Experimental acoustic flight tests have been performed to specifically assess noise levels from prototype UAM aircraft [225]. Moreover, the frequency of occurrence of UAM operations at scale is predicted to be much higher than conventional aircraft operations, but standard metrics fail to discriminate the impact of variations in the distribution of sound energy in time in human perception [226]. The relationship between noise exposure and human annoyance has been first investigated by [227]. Aviation noise has traditionally been found to result in higher annoyance than other modes of transportation [228]. Such perception extends to novel aircraft types. For instance, [229] found evidence for a systematic difference between the annoyance response generated by the noise of sUAS and road vehicles. Many perception studies exist about airport noise because of "traditional" community complaints. Perception studies on helicopter noise are available as well but are less extensive (for reasons such as procedure specificities, lower number of operations, etc.). However, the applicability of such studies to UAM is unclear. In addition to annoyance, the use of other measures such as audibility and noticeability has been considered to account for the continuum of human response levels, which are a function of spatial and temporal variations of natural and human-made background (ambient) noise [160]. Research about the impacts of aircraft noise has also identified adverse health effects such as sleep disturbance, academic impairment in children and cardiovascular disease for people living near airports [230], which might also be the same for UAM noise. To mitigate the UAM noise impacts and increase the likelihood of acceptance by the general public, noise related objectives have been considered in studies for vertiport site selection, UAM route design, and trajectory planning [48, 222, 223]. In summary, UAM aircraft have very different noise sources than traditional transport aircraft or helicopters and will operate in a dense urban environment with unique sound propagation patterns, requiring a deeper understanding about these new noise profiles and the response to them.

6.3.2 Gap analysis

UAM operations including passenger-carrying, cargo delivery, and other non-transport operations should support the sustainability goals of localities by following community driven guidance through a sustainable urban mobility plan (SUMP) or a similar alternative. Cities need to have tools available to design, develop, and deploy UAM operations in line with their objectives and needs. Another critical gap is the interaction with wildlife living in areas of UAM operations. Additionally, there is a need for a strategy and framework for community engagement before UAM noise

concerns arise. In terms of UAM noise assessment, some identified gaps include the lack of UAM aircraft noise data during development, the need for psychoacoustic tests to understand human response, and the uncertainty surrounding the effectiveness of existing noise metrics. Researching and understanding acoustic data from UAM aircraft, conducting community noise impact studies, developing standardized processes for ambient noise measurement, validating models for audibility, noticeability, and annoyance to UAM aircraft noise, and developing strategies to mitigate UAM noise impacts are necessary steps towards increasing the likelihood of public acceptance.

6.3.3 Open research areas

1. The repetitive nature of UAM may lead to a different noise perception than that of traditional airport noise (in public situations/cluttering), what is the visual impact on the auditory perception?
2. What metrics are most suitable to represent the annoyance response to UAM?
3. What metrics are most suitable to quantify the noise exposure of UAM aircraft?
4. What metrics are most suitable to represent the community noise impact from UAM operations?
5. What models and tools are most suitable for UAM noise assessment?
6. Are the adverse effects of aircraft noise different for UAM operations?
7. How can UAM infrastructure planning and operation strategies contribute to mitigate UAM noise impacts?

6.4 Safety and the societal perspective

To address societal acceptance for safety of UAM, it is worth differentiating between safety and safety perception and then to assess perception for all the different impacted stakeholders. While the concept of safety is well founded and accepted within the aviation community, outside that community it is worth considering the perception of safety. Keeping people safe and ensuring that people feel safe are two different challenges. People expect the service providers they interact with to pose little risk to their physical, mental, or financial health; therefore, news of incidents, which are a common occurrence for the aviation community, might induce the public to feel unsafe. While the collection of historical data on UAS flights can support reliability engineering and safety assurance, the perception of safety is very vulnerable and susceptible to sudden changes. Safety experts in UAM should look to implement programs that both improve the actual safety of their customers and

their perception of safety. Acceptance is dependent on the perception of safety and other aspects related to the benefits the innovation can bring. To identify benefits, it is necessary to assess who will be impacted. The “impacted stakeholders” in charge of accepting the UAM paradigm are those in the UAM industry (manufacturers, operators, service providers, etc.); UAM users; governments/regulators; as well as indirectly affected third parties (such as private individuals, environmental organizations, etc.).

6.4.1 State-of-the-art assessment

While there are multiple studies concerning the general acceptance of UAM applications, only few studies take into account UAM safety acceptance and perception. One such study was performed by EASA in 2021 [212]. Based on research, literature review, local market analysis, surveys and interviews, the study examined the attitudes, expectations, and concerns of EU citizens with respect to UAM. When encouraged to reflect upon consequences of potential UAM operations in their city, EU citizens want to limit their own exposure to risks, in particular when related to safety, noise, security and environmental impact. While safety concerns rank first, the study shows that citizens seem to trust the current aviation safety levels and would be reassured if these levels were applied for UAM. Differences in acceptance depend on the application (e.g., medical services and deliveries, rescue operations and public safety represent the applications with the highest acceptance levels). Safety is one of the main obstacles for UAM deployment, and acceptance challenges are expected for “nonurgent” usage (not lifesaving usage). Finally, social acceptance results from balancing the costs and benefits of a transportation system. Additional to safety requirements, also needs for affordability, accessibility, environmental friendliness, and economic viability must be fulfilled [205].

6.4.2 Gap analysis

Safety acceptance is currently reliant on the public perception of traditional aviation safety standards. Due to the lack of current operations and related data as well as the fact that the UAM ecosystem will comprise new technologies and safety acceptance – at least in the beginning – has to be gained without relying on existing standards or experience from traditional commercial operations; therefore, the respective concerns of the impacted stakeholders, with regards to roles and responsibilities of UAM agents, privacy and (cyber) security, transformation, communication, safety promotion and culture and many more topics, have to be newly assessed and taken into account when developing UAM technologies and new technical or operational

regulations. Further research and comprehensive studies are required to fully understand the misgivings and possible misconceptions of the public in order to develop adequate communication strategies and other tools that encourage UAM safety acceptance.

6.4.3 Open research areas

1. What are the main concerns of impacted stakeholders with regards to UAM safety in general as well as towards certain UAM-specific technologies and procedures/operations?
2. How can we ensure coordinated actions between all authority levels, influence citizens to trust those authorities equally, and expect all levels to be involved in decision-making?
3. How can we ensure that UAM has a perceived safety level equivalent to that of current aviation operations despite its reliance on new and different technologies?
4. Can demonstrations and pilot projects encourage safety acceptance? If so, in what way?

7 Scientific assessment engineering process

As work progresses in all areas to identify, understand, and mature products relevant to the UAM Scientific Assessment, the IFAR working group on UAM is investigating the application of core systems engineering processes to support the capture and organization of those products. As defined by the International Council on Systems Engineering (INCOSE): “*Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods*” [231]. Systems engineering processes span the complete lifecycle of desired products, encompassing the design of the system, management of the system technologies, development of the system products, and eventually closeout of the system products. These system engineering processes for UAM/AAM are foundationally sound, referencing systems engineering guidance such as the NASA Systems Engineering Handbook [232], but are being tailored to meet the needs of our IFAR UAM working group member states.

For the IFAR UAM working group, the efforts will concentrate on the identification and understanding of UAM concepts and associated system requirements captured under system design processes. System design processes can be decomposed into four primary tasks, namely:

1. Stakeholder Expectations: define the needs, goals, and objectives of the system, capture relevant use cases based on a vision of UAM concepts, and apply overarching constraints to potential solutions.
2. Requirements Definition: define system-level behaviors necessary to meet the captured needs of the system and fulfill the concepts vision.
3. Logical Decomposition: derive performance requirements and data flow across candidate system elements outlining the initial structure for a system architecture.
4. Design Solution Definition: develop candidate designs, assign system elements to physical components, and evaluate against the concepts and stakeholder needs.

These primary tasks of the system design process are intended to build upon each other and mature the system to capture a consensus design. The process is also meant to be iterative to support refinement of the concepts, use cases, and needs of the system based on research results and interoperability testing of candidate system architectures. In alignment with the research nature of the IFAR UAM working group (and as demonstrated by the scope of the one-page descriptions in Sect. 3), the majority of the work will fall under the Stakeholder Expectations and Requirements Definition tasking.

Due to the complex nature of the overall UAM concept and underlying potential for myriad solutions, The IFAR UAM working group is also investigating the adoption of model-based systems engineering (MBSE) processes. MBSE is defined as: “*The formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases*” [233]. Using an MBSE approach facilitates the capturing of potentially disparate UAM concepts and use cases across IFAR member states to help identify common architecture elements through the traceability of system-level requirements to system needs.

8 Conclusion

A key focus of this first Scientific Assessment is to establish a rigorous and efficient process for providing consensus research findings to the ICAO. The three focus areas covered in this document are UAM technology, operational aspects, and societal acceptance. Main outcomes are understanding where the research is needed related to airspace operations, aircraft design, social acceptance, safety, security, autonomy, maintenance, and infrastructure. Additionally, overarching architecture with capabilities to support airspace operations, onboard automation, and CNS infrastructure.

The scientific assessment has identified key gaps where research is needed to set up requirements to enable UAM/AAM at large. One of the key challenges is to ensure scaled operations are possible without compromising safety. The scaled operations require research related to manufacturing at high scale, maintenance, and airspace operations that will not overload the existing air traffic control. In addition, airspace, aircraft, and infrastructure requirements to operate under both nominal and off-nominal situations must be well understood and harmonized for industry's benefit. Understanding critical off nominal and contingency situations and developing technologies and procedures to address them is also an important area of research. In order to accommodate scalability in a safe manner, higher levels of automation are required, and human-automation integration remains a critical area of research.

Appendix: A Glossary of terms

Term	Description of Term
Advanced Air Mobility (AAM)	A transportation system that transports people and property by air between two points in the NAS using aircraft with advanced technologies, including electric aircraft or electric vertical take-off and landing aircraft, in both controlled and uncontrolled airspace
Air Metro	An UAM market that resembles current public transit options such as subways and buses, with predetermined routes, regular schedules, and set stops in high-traffic areas throughout each city
Air Taxi	An AAM market providing point-to-point passenger transportation and not operated on regular schedules or routes
Autonomy	The ability of a system to achieve goals while operating independently of external control. Autonomy requires self-directedness to achieve goals and self-sufficiency to operate independently
Collision Avoidance	The maneuver of an aircraft after becoming aware of conflicting traffic. This capability is currently achieved by one of the following means: visual observation, Airborne Collision Avoidance System alert, or traffic information provided by Air Traffic Control
Communication-Navigation-Surveillance-and-Information (CNSI)	The elements of the air traffic management (ATM) system associated with real time acquisition and transmission of operationally relevant information on aircraft position, identification, meteorological phenomena, system status, and ATM control actions. It includes the parts of the aircraft system associated with control of own aircraft position using acquired data

Term	Description of Term
Concept of Operations (ConOps)	A description of the overall high-level concept of how the system will be used to meet stakeholder expectations, usually in a time sequenced manner. It describes the system from an operational perspective and helps facilitate an understanding of the system goals. It stimulates the development of the requirements and architecture related to the user elements of the system. It serves as the basis for subsequent definition documents and provides the foundation for the long-range operational planning activities (for nominal and contingency operations), and it provides the criteria for validation of the system
Electric Vertical Take-off and Landing (eVTOL)	An aircraft that uses electric power to hover, take off, and land vertically. These aircraft include a variety of configurations, such as Lift + Cruise, Multiple Rotor, and Tilt Wing
Environmental Sustainability	The rate of renewable resource harvest, pollution creation, and non-renewable resource depletion that can be continued indefinitely
Fully Autonomous Aircraft	An aircraft that can perform all necessary piloting functions, including determination of a new course of action in the absence of a predefined plan, while operating independently of any external control, including control from a human pilot, aircraft operator, and/or multi-aircraft supervisor
Infrastructure	The basic physical and organizational structures and facilities (e.g., buildings, roads, power supplies) needed for the operation of a society or enterprise
Innovative Air Mobility (IAM)	The safe, secure, and sustainable air mobility of passengers and cargo enabled by new-generation technologies integrated into a multimodal transportation system
Maintenance	Any repair, adaptation, upgrade, or modification of National Airspace System equipment or facilities, including preventive maintenance
Noise	Sound that is unwanted. Noise has both an objective, physical component, as well as a subjective component that takes account of a person's individual perception, or reaction, to a sound
Provider of Services for Urban Air Mobility (PSU)	An entity that assists UAM operators with meeting UAM operational requirements to enable safe and efficient use of UAM corridors and aerodromes. This service provider shares operational data with stakeholders and confirms flight intent
Regional Air Mobility (RAM)	A part of AAM that focuses on building on existing airport infrastructure to transport people and goods using innovative aircraft that offer a huge improvement in efficiency, affordability, and community-friendly integration over existing regional transportation options for trips of approximately 50 to 500 miles
Safety	The state in which the risk of harm to persons or property damage is acceptable
Safety Management System	An integrated collection of processes, procedures, policies, and programs that are used to assess, define, and manage safety risk

Term	Description of Term
Scalability	The ability of a system to maintain its performance and function, and to retain all its desired properties when its scale is increased greatly, without causing a corresponding increase in the system's complexity
Simplified Vehicle Operations (SVO)	The use of automation coupled with human factors best practices to reduce the quantity of trained skills and knowledge that the pilot or operator of an aircraft must acquire to operate the system at the required level of operational safety
Standard	A manufacturing, design, maintenance, or quality standard or method, technique, or practice approved by or acceptable to a civil aviation authority. It includes, but is not limited to, standards for aircraft design and performance, required equipment, manufacturer quality assurance systems, production acceptance test procedures, operating instructions, maintenance and inspection procedures, identification and recording of major repairs and major alterations, and continued airworthiness
Uncrewed/Unmanned Aircraft System (UAS)	An uncrewed aircraft and its associated elements related to safe operations, which may include control stations (ground, ship, or air based), control links, support equipment, payloads, flight termination systems, and launch/recovery equipment
Urban Air Mobility (UAM)	The vision of a safe, efficient, convenient, affordable, and accessible air transportation system for passengers and cargo that revolutionizes mobility around metropolitan areas. This vision includes everything from small package delivery drones to passenger-carrying air taxis that operate above populated areas. UAM is a subset of the broader vision for AAM
Urban Canyon	Locations in the urban setting between buildings, such as where a street is flanked by tall buildings. Weather in urban canyons can differ from the surrounding areas outside, particularly with respect to temperature, wind patterns, and air quality
Vertiport	An area of land, or a structure, used or intended to be used, for electric, hydrogen, and hybrid VTOL aircraft landings and take-offs and includes associated buildings and facilities
Weather-Tolerant Operations	Operations resistant to the effects of severe weather conditions, including visibility, winds, turbulence, precipitation, and icing

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